University of Southern Queensland

Faculty of Engineering and Surveying

Automatic Splint to Prevent Self-Harm in Autistic and Brain Injured People.

Dissertation by

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In fulfilment of the requirements of a

Bachelor of Engineering

(Instrumentation and Controls Systems)

Final Report Due

November 29 2015

Abstract

This dissertation is aimed at providing a less restrictive alternative to applying restrictive splints to people who display self-injurious behaviour often seen in people with severe autism or brain injuries.

An electronic method of controlling an elbow jointed splint is explored, designed, built and tested. The final product, the Dynamic Splint Device (DSD) is a self-contained electronic joint that utilises an electromagnetic brake controlled by an Arduino microcontroller electronics board. Sensors measuring elbow joint rotational velocity, total fist acceleration and bending moments are used to predict potential impact forces. The device will reduce injury by applying a braking force to the joint when the predicted impact is greater than an adjustable set-point.

The electronic ratchet developed as part of the braking system has allowed a sense of not being restrained, as the arm is not restricted from moving to a more open position. The ratchet has also increased the battery life of the DSD.

Legally, restraints are required to be the least restrictive available. The DSD has the potential to revolutionise the care of people displaying Self Injurious Behaviour (SIB) by reducing the need for full restraint. It allows movement in a safe manner, restores civil liberties, and allows better therapy when compared to full restraint devices currently available on the market.

Allowing health professionals and carers to build this device is integral to the design. Open source coding, 3D printable parts and off the shelf components allows anyone with a computer and a 3D printer to make the DSD, with the only limitation being that profit is not made.

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Mark Richardson

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Acknowledgements

I would firstly like to acknowledge Evan Williams for providing me with the initial idea to develop this device, my wife and children for putting up with me and supporting me throughout this final dissertation, and also throughout the last 10 years of part time study.

Acknowledgement also goes to my friends and extended family who have contributed more to this dissertation than they realise. Without support from family and friends, I would have found it difficult to keep focus like I have. Friends and family have also been used as an essential sounding board on many occasions.

I would also like to thank Andrew Maxwell, my dissertation supervisor, for providing me with the guidance required, and for giving me ideas which led to better outcomes.

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Nomenclature

α	Acceleration
Δ	Difference
σ	Stress (Force/Area)
ε	Strain
Ω	Resistance in Ohms
θ	Angle in Radians (unless degrees is specified)
τ	Torque
ω	Angular Velocity in m/s
A	Current in Amperes
$\mathbf{A_x}$	Acceleration in the x direction (x, y and z directions are used)
E	Elastic Modulus (Stress / Strain)
F	Force
F	Capacitance in Farads
g	G-Force. Equivalent to 9.81 m/s^2
GF	Gauge Factor (Ratio of resistance change / Strain)
Hz	Hertz in Cycles per Second
I	Moment of Inertia
J	Kinetic Energy
kg	Kilograms
L	Length
m	Mass
N	Newton Force. Equivalent to 1 $kg \cdot m/s^2$
P	Impulse. Units in N·s
rad	Radians
s	Seconds
t	Time
v	Velocity
V	Voltage
W	Watts

Glossary of Terms

bps	Bits per second
CAD	Computer Aided Design
CC	Creative Commons
DC	Direct Current
DSD	Dynamic Splint Device (This project)
ERF	Electrorheological Fluid
ET	Essential Tremor
IDE	Integrated Development Environment
IMU	Inertial Measurement Unit
JHA	Job Hazard Analysis
MOSFET	Metal Oxide Semiconductor Field Effect
MRF	Magnetorheological Fluid
MSDS	Material Safety Data Sheet
PID	Proportional, Integral and Derivative Control Algorithm
PLA	Polylactic Acid. This is the 3D printable polymer used.
PWM	Pulse Width Modulation
SIB	Self-Injurious Behaviour
SMA	Shape Memory Alloys
SSI	Synchronous Serial Interface
TSD	Therapeutic Shock Device
USB	Universal Serial Bus
WHS act	Work Health and Safety Act

Chapter 1. – Introduction

Self-injurious behaviour (SIB) is a devastating condition that typically affects people with severe autism and brain injury. SIB involves multiple self-harm behaviours, including sufferers inflicting head injuries, which can lead to broken cranial bones and even acquired brain injuries in severe cases. Many forms of treatment are available for this condition, however in extreme cases where other therapies are not working, it is necessary to apply restraint type splints to prevent injury.

This project explores the ways in which we currently attempt to reduce injury, brainstorms ways in which we can do this better and then develops a Dynamic Splint Device (DSD) which restrains the wearer when impact is being attempted and allows free movement at all other times. From this point on ‘the device’ will be referred to as ‘the DSD’.

1.1 Background

Studies show that Self-Injurious Behaviour (SIB) Affects between 4% and 12% of children with severe intellectual disabilities (Matson, Andrasik & Matson 2010). Research has also shown that there is currently nothing available to help people with this condition that does not include tying body parts down as a form of mechanical restraint, ingesting drugs to change the behaviour, or the use of aversive behaviour therapies including electrical shock.

In Western Australia, the Code of Practice for the Elimination of Restrictive Practices (Commission, Disability Services 2014) states that restraints should be a last resort and it must be proven that all less restrictive practices have been evaluated and cannot be applied.

There are limited choices for a using a least restrictive option when a restrictive device is required, therefore this project addresses the gap and aims to develop a restrictive splint that is only restrictive when required and will therefore become the least restrictive option available.

1.2 Motivation

The motivation for this project comes from the dilemma faced with carers on how to prevent people with self-injurious behaviour harming themselves or others. When a patient exhibits challenging behaviours, as a last resort the people are put in restraint, however if complete immobilisation is used, once in restraint the arms cannot be moved at all, which limits development, limits the progression of behaviour therapies and removes the dignity and freedom during this period.

Another motivation has been that restraint devices available range from complete immobilisation using beds or chairs, to slightly restrictive cuffs that can reduce the SIB under control without restricting movement (Federal Drug Administration Board (FDA) 2014). The problem that carers face is that each of these devices are only effective for certain conditions and if conditions change, then either the device is ineffective, or the device is too restrictive, neither of which are in the best interests of the client (Williams 2015).

1.3 Aims

The aims of this project are to;

- Research available devices and technologies to find what is used currently to prevent harm in people with challenging behaviours such as SIB and also research technologies that may be utilised to help prevent harm.
- Design, build and test a splint device that can electronically controls a device to minimise harm by detecting when harm is about to occur or has occurred and only restrict movement during these times.

1.4 Objectives

1. Complete research on self-harm to gain insight to help develop the DSD.
2. Determine the amount of force/velocity required to cause harm, versus the speed required to use an arm normally for every-day tasks.
3. Research methods to detect acceleration and methods to slow down the acceleration to determine the most practical methods to detect and control the elbow joint speed.

4. Model the forces involved in the elbow joint of the arm and develop a model to control the forces via a braking mechanism.
5. Develop electronics to amplify the velocity sensor so that the sensor can be used by a microprocessor circuit.
6. Either program a microprocessor system, or electronically create a control scheme to control the braking of the arm proportionally dependent upon speed via an adjustable setting, with the input being the velocity sensor and the output being a braking mechanism.
7. Create a mechanical system to house the elbow joint and electronics.
8. Test and evaluate the DSD.
9. Submit an academic dissertation on the development of the DSD.

1.5 Summary

This dissertation aims to develop a device which can be used instead of a fixed mechanical restraint for people with SIB. The device will only restrain someone when it detects that they are trying to harm themselves and is free to move otherwise.

The research and development of a device is expected to change the way that restraint is used to treat people with SIB and a great outcome would ensure that dynamic devices be the first choice for people needing to be put in restraints.

The outcomes of this project will be used to further develop effective devices along the same principles which can be made accessible to anyone who requires it.

Chapter 2. - Literature Review

The following literature review covers the topics that affect the development of the DSD. Firstly existing technologies are explored to determine what else is being designed to address the issue, followed by a review of component technologies that are required in the device.

2.1 Self-injurious Behaviour (SIB)

Self-injurious behaviour describes non-accidental behaviour which inflicts damage or destruction of body tissue, which is carried out without suicidal intentions. Between 4 % and 12 % of children with severe intellectual disabilities (Matson, Andrasik & Matson 2010) exhibit self-injurious behaviour which may present as face slapping, head punching, head banging, or other behaviours which cause harm. In most cases behavioural therapies or treatment of underlying physical illness stops the self-injurious behaviour.

As explained by Matson (2010), the treatment of SIB behaviour is complex and should be individual for each patient. There is no single solution which cures the behaviour and the use of drugs or mechanical restraints is not a solution to the SIB behaviour, but when other treatment fails to stop the SIB behaviour, restraint may be used to protect the person. It is important that patient protection is the aim and not as a solution to stop the behaviour.

This highlights the fact that using restraint is not a treatment for SIB, but a protective device when all other treatment has proven to not stop the behaviour. Therefore the DSD should only be used in conjunction with health professionals as part of a holistic treatment plan.

2.2 Existing Standards/Best Practices/Ethical Issues

A key principle of medical ethics is that a patient's autonomy should be respected, therefore there are ethical issues surrounding the use of restrictive splints for restraint purposes, as it often takes away a person's autonomy.

In Australia the use of restraints is legislated. In Western Australia, the following are some of the acts and standards that apply;

- *Mental Health Act 2014,*
- *National Standards for Disability Services 2013*
- *Charter of Human Rights and Responsibilities Act 2006*
- *Disability Discrimination Act 1992*
- *National Framework for Reducing and Eliminating the use of Restrictive Practices in the Disability Services Sector 2014*
- *Disabilities services Act 1993*
- *Children and Community Services Act 2004*
- *Equal Opportunity Act 1984 (WA)*

These acts, charters and standards should all be consulted in the use of restraint.

The Western Australian Government's Office of the Public Advocate has put out a position statement with regards to protecting the human rights of adults with decision-making disabilities (Office of the Public Advocate, Governemnet of Western Australia, Department of the Attorney General 2013). This position statement explains that because the use of restraint is a major infringement on a person's civil liberty, it should only be used as a last resort and all alternative methods should have been either explored and failed, or inappropriate. Also, restraint can only be used as part of a holistic intervention plan developed and approved by a treating team in consultation with the family with the consent of a guardian. The position statement also states that restraints can only be used if less restrictive alternatives have been tried and the proposed restraint is the least restrictive form available.

Legislation also exists in Western Australia in the *Health Act 2014* (Government 2014), which states under clause 228, that the degree of force must be the minimum that is required and the person must be treated with dignity and respect. The act also states in clause 229 that bodily restraint must only be used in accordance with an oral authorisation, or a bodily restraint order, with a current penalty of $6000. Oral authorisation may only be given by a medical practitioner, mental health practitioner or the person in charge of a ward at an authorised hospital and is only an emergency measure prior to obtaining a bodily restraint order (a bodily restraint order must be obtained within 30 minutes of an oral authorisation, otherwise restraints must be removed). This legislation does not cover the ongoing use of restraints, which seems to be managed by Disabilities Services in Western Australia by a code of practice.

The Code of Practice for the Elimination of Restrictive Practices (Commission, Disability Services 2014), is part of a Positive Behaviour Framework set out by the disabilities commission and provides a basis to develop operational policy and guidelines to eliminate the use of restrictive practices for people with SIB. This code aligns with the new Standards for Disability Services which has been adopted by all states. The purpose of this code is to raise the awareness of the human rights of people with a disability and the eventual elimination of restrictive practices for people with challenging behaviours. It also provides a framework for ensuring that restraints are used as a last resort and only if approved by the service providers Positive Behaviour Support Panel. This panel must be convinced that all less restrictive practices have been evaluated, cannot be applied and that the restrictive practice is considered in the context of a positive behaviour support plan and a person-centred plan.

The development and usage of an electronically controlled device will ensure that in the instances where there is a requirement for a restrictive device, that the freedom of movement is maximised. Therefore the ESD will be the least restrictive device available that adapts to the behaviour of the wearer. If successful in the treatment of people with challenging behaviours, then the use of this device will guarantee that restraint is only applied when required and allows complete freedom of movement otherwise.

2.3 Existing technologies

There are two different areas where existing technologies are relevant. Firstly technologies that address restricting self-harm and secondly the technologies for elbow joints to restrict movement.

2.3.1 Self –injurious Behaviour (SIB) treatments

Over the years, SIB has had many treatments. The basis of most treatment is psychological. Included in the treatments has been the use of adverse stimuli such as electric shock, water misting, exposure to aromatic ammonia and physical restraint (Matson, Andrasik & Matson 2009). This adverse stimuli is used as part of the treatment, however the treatment of SIB is complex and not all treatments work on all people.

The only automated device found for the treatment of SIB has been adverse stimuli devices such as an electric shock device that is applied when impact has been detected (Salvy et al. 2004). The device applies an 'adverse stimuli' and although controversial, has had some success in reducing SIB frequency.

Many other treatments exist and this review does not attempt to fully explore all of the treatments available, but attempts to explore the technologies used when mechanical restraints are required. Nothing could be found that resembled a smart restraint. There have been many studies completed (Oliver et al. 1998) where an adjustable style splint has been used which allows varying degrees of freedom. The Prime$^{(TM)}$ Elbow splint by Orthomerica has been used to allow the degree of restraint to be systematically and easily reduced as the SIB behaviour improves. This splint is designed for limiting postsurgical or post-injury arm motion and rotation. Movement at the elbow can be increased or decreased in 30 degree increments allowing for no flexion to full flexion movement. The trials that Oliver completed showed better results than fixed splints in most cases, even when the full movement was allowed. Therefore in some cases, a splint with full movement works, even though it is not restricted in movement. Something else clear in this study is that not all patients respond the same, so each case must be assessed individually.

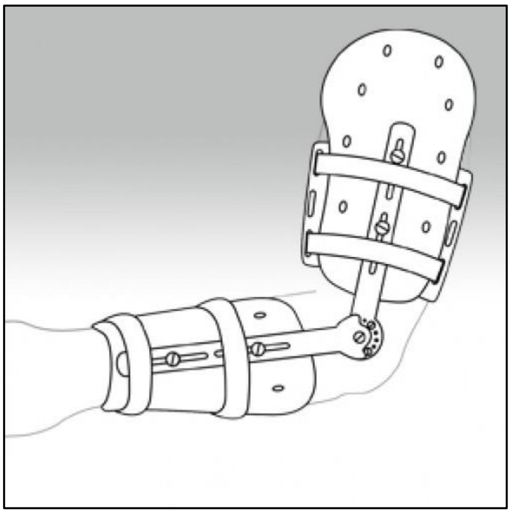

Figure 2-1: Prime Elbow Splint by Orthomerica

After extensive research, as well as conversations with health professionals working for the Disabilities Services in Western Australia (Williams 2015), it has proven difficult to find any splint device which is designed to automatically adjust to reduce the harm when an impact was imminent and gave free movement otherwise.

2.3.2 Elbow joint movement technology

Research was completed to find an elbow joint that existed which would brake the arm and could be easily worn.

The devices found utilised motors, hydraulics or pneumatics for the purpose of rehabilitation, assisting and human amplification (Gopura, Kazuo & Bandara 2011). These devices are all designed to give more control and strength to the human body, or are designed to assist in rehabilitation.

At a recent robotics conference, a study was published (Matsumoto et al. 2014) on a passive exoskeleton device to assist people with essential tremor (ET). The movement of ET patients could become debilitating while trying to accomplish basic tasks like eating. The device was designed to reduce compensatory movement during simple tasks. The device is used to constrain the tremors passively without the need for motors. This is performed by only allowing a movement along a certain track, with the forearm rotating when the elbow joint is bent and is designed to allow the wearer to eat while reducing the effects of the tremors by restricting all movements other than those required along the path for eating. This device was one of the few passive devices found, however has a specific use and therefore found to be not applicable to the DSD.

In a study of resistive torque mechanisms for rehabilitation exoskeletons (Chetran et al. 2014), rotational Electrorheological Fluid (ERF) and Magnetorheological Fluid (MRF) brakes were studied with respect to the elbow joint to determine torques developed and explores the advantages and disadvantages of using rotary ERF brakes. ERF behaves as a Non-Newtonian fluid when an electric current is passed through the liquid. Mechanical systems have been developed which develop torques utilising this technology. These devices can be placed directly on the elbow joint, however this study concluded that although these ERF devices have the advantage of developing the torque directly into a resistive joint, they are not commercially available and must be designed especially for a maximum required torque. The study also showed that at the moment, the cost is making these unaffordable for a viable implementation into the structure of an upper limb exoskeleton.

The research completed has found no devices that dynamically brake for the intention of reducing harm from SIB. The research did find resistive torque mechanisms that could be utilised, however most of these devices are either expensive, not of the wearable size, or are inappropriate. ERF and MRF fluid brakes would be ideal to use as the braking mechanism of the DSD due to lightweight size for the amount of torque, however after extensive research and many phone calls, only one device suitable was found in the United States which was a demonstration unit that had not been commercialised. Therefore with the premise of the DSD being made form off the shelf components, the ERF brake is not suitable at this time. A request has been made to obtain this demonstration ERF unit so that it can be evaluated; however it is not clear whether the unit will be made available at the time this preliminary report was written.

2.4 Velocity Sensor

The measurement to determine impeding impact will be arm velocity. The impact will be inferred from the rotational velocity of the elbow joint, as the DSD is only for the elbow joint. It is also understood that impact from a fist is an accumulation of speed of the elbow joint as well as the shoulder joint. Therefore as well as velocity measured at the elbow joint, the total linear velocity will also be measured.

2.4.1 Rotational velocity

In exoskeleton design, encoders are commonly used for rotary speed measurement; with direction and speed being able to be determined, usually from a Synchronous Serial Interface (SSI) output for a binary coded absolute precision data (Avago Technologies 2015). A search was completed at on online store (RS-ONLINE 2015) for ‘Rotary Encoder’ where 532 rotary encoders were found with minimum pulses per revolution of 400[1]. Low profile encoders all were either greater than $200, or did not have the required resolution. This renders them unsuitable for this project and will not be considered further.

Hall Effect sensors, capacitive and inductive sensors can all be used to measure speed when used with a toothed gear and can determine speed by counting the number of times a tooth is detected on a toothed wheel. These sensors can be used if a metal toothed rotating element is utilised such as the devices from Honeywell (Honeywell 2014) which can come in sizes from surface mount to stainless steel threaded sensors.

Optical encoders are used throughout the computing industry to read the position of disk drives, in robotics and elsewhere. The advantage of optical devices is that there is no requirement for ferrous parts. An encoder disk can be created with dark/light lines that are picked up by the optical encoder. With this type of encoder, the distance between the stripes determines the resolution and can be made to suit the application. Optical encoders do have sensitivity to dirt and dust so must be kept clean.

Each of the above speed detection devices have either poor resolution, are expensive, or they are too bulky. Another two options are either using a precision rotary potentiometer which can be obtained for under $10, or using an electronic gyrometer. The problem with a gyrometer is that it will measure the total angular velocity rather than just the angular velocity of the elbow joint and is therefore not suitable for the elbow joint only. This then leaves the potentiometers which can give a linear output for position. A precision potentiometer should be used which has better resolution than a typical wire wound potentiometer.

Therefore for simplicity, a high precision potentiometer will be used and integrated into the elbow joint.

[1] Since we are only measuring around 90 degrees and with a minimum of 1% resolution, we would need 100 pulses per 90 degrees, which is 400 pulses per revolution.

2.4.2 Total Velocity

In the last few years, sensing hardware developments have made available miniaturised inertial and magnetic sensors such as accelerometers and gyroscopes. These sensors are not only common in robotics and biomechanics, but have also been used extensively in mobile phones and cameras due to their low cost, small weight, ease of use and low power consumption. The only downside is that we are now required to estimate position from acceleration rather than measuring it directly, however the advantages are that the sensors are no longer required to be mounted on the pivot point. It can also be difficult to interpret the components due to gravity compared to the component related to the motion of the object (Caroselli, Bagala & Capello 2013).

Accelerometers measure the acceleration caused by motion, as well as gravity. When the sensors are standing still, they measure gravity pulling down on it and can therefore measure tilt angles by using the 3 degrees of motion in the X, Y and Z planes.

A gyroscope will allow three-axis angular rate of angular change. An example is the ST Microelectronics L3G4200D which is a low power (ST Microelectronics 2010) stable device capable of providing a real-time measured angular velocity through a digital interface (I^2C/SPI) capable of measuring rates at a minimum of +- 250 degrees per second (dps) up to +-2000 dps (user configurable). EBay currently has these units selling for under $10.

2.5 Speed Control/Brake

Speed control of robotic joints can be achieved either from active drive elements such as motors, or from resistive elements such as a friction brake. The DSD only requires the braking force, however both active drive and resistive elements have been reviewed and they can both provide a braking torque.

2.5.1 Active Drive Elements

Active drive elements include electric motors, pneumatic cylinders, hydraulics and hybrids of these. One such hybrid found uses pneumatic electric hybrid actuators with Bowden cables which mimics the way muscles work together to rotate an arm (Tomoyuki Noda, Ugurlu & Morimoto 2014). This device has many elements incorporated to drive the joint. This has been seen as too many moving parts to be durable in a device which will take some impacts.

Robotics usually favours servo motor drives (Tar, Veres & Cserey 2006) for robotics due to the ease of controllability and immediate feedback. The servo motor tries to move to the intended position until it is reached, however there is no information about the actual position. On the other hand, stepper motors have constant moment and excellent tuning moment/weight rate. Stepper motors are used for the low speed high accuracy movements, however are much more complex to control (Melkote et al. 1999).

Even though the DSD only requires braking torque, the stepper motor was still considered due to its controllability. One downside to using a stepper motor is that to have the holding torque to stop or impede a grown person's strength would mean that the device could also have the potential to overpower and drive the arm against someone's will. This is seen as a safety issue in case of malfunction. It also required a much larger motor than for one used to simply assist movement. For instance, an online store (RS-ONLINE 2015) has stepper motors capable of around 5 N·m which cost between $300 - $400, with a weight starting from 2.8 kg. This is too heavy to be wearable and is also too expensive to incorporate into the DSD.

2.5.2 Resistive Elements

Conventional Braking system which include drum brakes and disk brakes were considered, however due to the speed of response, increase in weight and brake pad wear, these were excluded from the decision.

Eddy current braking is being used within the automotive and locomotive industries to assist in braking; however they cannot be used alone due to their low braking torque generation in the low speed region (E Simeu 1996). Studies into the improvement of low braking torque at low speeds have shown that this can be improved by the use of different AC waveforms rather than DC (Karako, Afzal. & Park 2014), however the research is in its infancy and also requires the addittion of extra electronics to create AC waveforms and so has been disregarded for use in the DSD.

A recent review into locking mechanisms for robots published in the IEEE Robotics & Automation Magazine (Plooij, Mathijssen & Cherelle 2015) compares the locking devices that have been used in robots. It compares mechanical locking devices, friction locking devices and singularity locking devices. The review discusses each device category and uses many categories for comparison. The comparison highlighted that of the braking devices used to control braking torque, electromagnetic brakes are one of the better conventional locking devices. This review also regards piezo actuators as one of the better mechanism if low power and size is important.

Piezo actuators use the piezo effect of a force creating a voltage, in reverse. A voltage can create a force in a piezo actuator. These actuators are stacked to drive a braking mechanism (Plooij, Mathijssen & Cherelle 2015). After trying to find piezo braking mechanisms in industry, it is clear that these devices are yet to be commercialised. Piezo actuators could be found (KC Kinetic Ceramics, inc 2015) (PiezoSystem Jena 2015), however actuators integrated into a brake mechanism could not be found other than in academic papers (Toyama & Yonetake 2007). Other searches revealed ultrasonic motors within the hands of robots in low power situations only (Tang, Sugano & Iwata 2011).

Magnetic Particle brakes were also investigated. These offer good torque control, simple design and available commercially, however an 8 N·m device weighted over 3 kg (Sterling Instruments 2015) and a 7 N·m device weighed 3.2 kg (Placid Industries 2015) which is not a wearable weight.

Shape memory alloys (SMA) such as Flexinol^{TM} have been used for assisting muscles (Ammar et al. 2010), in which an alloy is used which experiences change in shape and hardness when heated, generating a force in the process. These devices can generate large forces when resistance to its movement is encountered and can recover large strains. These have been successfully used to mimic muscle contraction (Ammar et al. 2010), however the articles reviewed have used these metals to help the contraction rather than impede contraction. Tests on Flexinol^{TM} (Ali, Wahied & Gihan 2014) show that the alloy has excellent properties for use in robotics, in that the actuation is silent, no electromagnetic interference, high power to weight ratio, small physical size and lightweight. The wire temperature needed to get to around 90 degrees and the phase transformation took approximately 0.5 seconds to respond mechanically to the change in temperature. A paper which discussed the theory, performance curves and design problems of SMA actuators concluded (Kluszczyn´ski & Kciuk 2013) that SMA actuators could be used as a special non-standard drive when ultra-light mass and simple mechanical construction of power feed system is required.

Electro-Magnetic brakes are common in robotics, have good linearity, are simple devices and are commonly available. Electromagnetic brakes build up a magnetic field when DC voltage is applied. The field attracts an armature disk to a brake coil carrier with a friction lining, which creates the braking torque. When the coil is de-energised, the shaft is free to spin. An internet search on commercial electromagnetic brakes, found an 8.5 N·m version weighing 0.42 kg (Mayr 2015) and is typical of the figures found. These electromagnetic breaks are therefore lighter than all other suitable brakes.

2.6 Controller

Controllers for the DSD were investigated, with the requirement to purchase an off the shelf controller/processor that is fully customisable with off the shelf components. The amount off custom electronics is to be kept to a minimum, as the intent for the project is for it to be easily made by anyone without electronic skills.

The two most popular open source customisable devices found are Raspberry Pi and Arduino. The Arduino has an 8-bit ATmega series microcontroller with a clock rate of between 8-16 MHz and 2-8 kB of RAM available. In contrast, the Raspberry Pi uses a 32 bit ARM processor, with a clock rate up to 1 GHz, with up to 512 MB of RAM. The main difference between the two being that Raspberry Pi is a micro-processor which runs LINUX, has a graphics driver, can plug keyboard, monitor and mouse straight in and therefore resembles a little computer, while the Arduino is a micro-controller and designed for embedded applications. The Arduino cannot run an operating system like the Raspberry Pi, but simply executes code as the firmware interprets it.

The advantages of the Arduino are that it has precise timing unlike the raspberry Pi, so better for real-time application. It also uses a lot less power (microwatts compared to watts in standby mode). The Arduino also has many “shields”, which are plug in devices. There are hundreds of shields available and include motor controllers, accelerometers, relay boards, Bluetooth modules, touch screens, as well as many others. Both of these controllers have a very large community of users that can be leveraged from and many websites are dedicated to the users of both of these devices.

A table below compares the main differences between the two. Sources are element 14 Raspberry Pi datasheet (Element 14 2015) and the Arduino datasheet (Arduino 2015).

Table 2-1: Arduino Vs Raspberry Pi

Feature	Arduino Uno	Raspberry Pi	Comment
Model	R3	Model B	
Processor	ATMega 328	ARM11	
Clock Speed	16 MHz	700 MHz	16 MHz processes 1 scan every 0.625 microseconds. Even if a command takes 8 clock pulses to execute, the speeds are much faster than the input and output devices which are being interfaced with
Flash	32 KB	External SD card	
RAM	2 KB	512 MB (shared with GPU)	
EEPROM	1 KB	N/a	
Minimum Power	42 mA (0.3W)	700 mA (3.5 W)	This is a significant difference for a battery powered device.
Input Voltage	7 to 12 volts	5 volts	
Analog Input	6 10-bit inputs	None	On board analogue inputs mean Arduino doesn’t require extra circuitry for analogue interfacing
Digital GPIO	14	8	
PWM	6	None	This PWM can be used for the brake actuation
TWI/I2C	2	1	
UART	1	1	
SPI	1	1	
Dev IDE	Arduino Tool	Linux, Squeak, IDLE, Scratch	
Ethernet	N/a	10/100	Not required
Audio Out	N/a	HDMI, analogue	Not required
Video Out	N/a	HDMI, composite	Not required

For the DSD, a full operating system that resides in the Raspberry Pi is not necessary, as the DSD controller just needs to read inputs and execute outputs, with addition of an optional Bluetooth interface to communicate to a phone interface. The low power, on-board input/output, ease of extra input/output interfacing via shields and application for real time processing along with the ease of use makes the Arduino the most suitable micro-controller to use.

2.7 Forces Causing Harm

To create a device which limits harm, research was completed in forensic science and biomechanics to find existing research which indicated the amount of force which would cause harm.

A study into the mechanics of bruising in living human objects found that they could determine the mechanical parameters required to cause contusions in a particular individual by using a striking implement (Geoffrey, Desmoulin & Anderson 2011). Many studies have been published which involve studies of contusions post mortem; however few of them study the mechanics of contusions in the living. This study was on contusions on the lower limbs and concluded that the Energy absorbed by the limb was a good correlation of whether the victim bruised or not and energy above 7 Joules caused contusion in most cases.

In another study completed on injury biomechanics (Hayes, Erickson & Power 2007), the impulse-momentum-principle with a factor which accounts for rebound effects at impact was used. The study shows that using this momentum principle and using impact duration from other published studies, the impact force can be calculated. The impulse equation is:

$$P = F \times \Delta t = m \times \Delta v \quad \text{(2-1)}$$

A study of head injuries caused by blunt force trauma (Sharky et al. 2012) in which an experimental model was used to assess the force required to cause damage to the head, revealed that the minimum force for the occurrence of a laceration was 4 kN.

In another study head impacts from robots were completed on dummies (Haddadin, Albu-Scha¨ffer & Hirzinger 2008), with forces that would fracture bone. The different parts of the head had differing forces to fracture, with the Maxilla being the least at 0.66 kN The other impact tolerances were Mandible = 1.78 kN, Zygoma 0.89 kN and the cranial bones (Frontal, temporal-parietal and occipital) at between 3.12 and 6.41 kN. Also, the average contact duration for the head impact was 0.01 seconds.

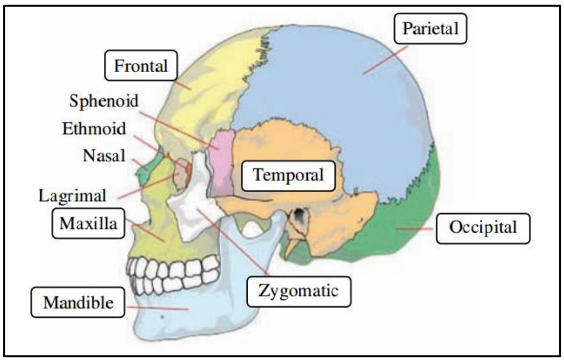

Figure 2-2: Cranial Bones

In a study of boxers (Walilko, Viano & Bir 2005), the average punch impact durations were again measured at 10 ms and with the effective mass of hand at 2.86 kg with a standard deviation of 2.03 kg. The effective mass of the hand was calculated using the conservation of momentum equation, where m_h is the effective mass of the hand, v_p is the hand velocity measured, while v_h and m are the velocity and mass of the test head;

$$m_h v_p = (m_h + m) v_h \quad \textbf{Equation 2-2}$$

Since this study was investigating the punching force of athletes, with the punch allowing upper body rotation to increase the punch velocity and hence effective mass, 2 kg has been chosen as the maximum effective mass that could occur with self-injurious behaviour and is seen as conservative for the circumstances.

From a study into exoskeletons (Gupta & O'Malley 2008), the maximum elbow strength was reported as being 72 N·m, however this value was a maximum value of an athletic adult male. In a study determining the strength of the elbow (Gallagher et al. 1997), it was shown that the peak torque values for flexion in a young person was 40 N·m. The mean values for extension were 58.9 N·m in a young age group (average age 25.6 with a standard deviation of 3.2).

Therefore to reduce the impact so as not to break a bone, the design will use a fist mass of 2 kg, an impulse time of impact of 0.01 seconds and will use a figure of 0.66 kN as the force that may break a cranial bone and the energy will need to be reduced to below 7 Joules.

2.8 Licensing

A decision was made to not Patent the DSD so that it could be available to anyone who could benefit from it. Patenting the DSD would cost tens of thousands of dollars and since profit will not be sought, patenting would not be beneficial. Research was completed to determine if protection at a low cost could be sought to ensure that no-one else could patent the DSD and also to ensure that everyone could make the DSD for free and distribute as needed, but not be able to make a profit from doing so.

2.8.1 Copyright

Copyright is automatically applied and protects the source code of a computer program; however it only protects the code and does not protect the idea within the program. Therefore if someone develops code that does exactly the same task with a different way of coding, then that will not be breaking the copyright (IP Australia 2015). Therefore copyright will automatically apply to the source code for the DSD and the 3D printed code which are the most important parts of the device.

2.8.2 Creative Commons

The creative commons license forms part of copyright law and is a way of formally allowing people to use copyright information with various restrictions. This is so that the public can have open access to the information and can also limit the way the information is disseminated. The intent of the DSD is to allow public access to the DSD, without someone else being able to profit from it. Having the DSD in the public domain also means that anyone wishing to improve on the source codes can, as long as they abide by the licence conditions. CC licencing can form part of licensing the computer code and the 3D modelling design, as well as this thesis.

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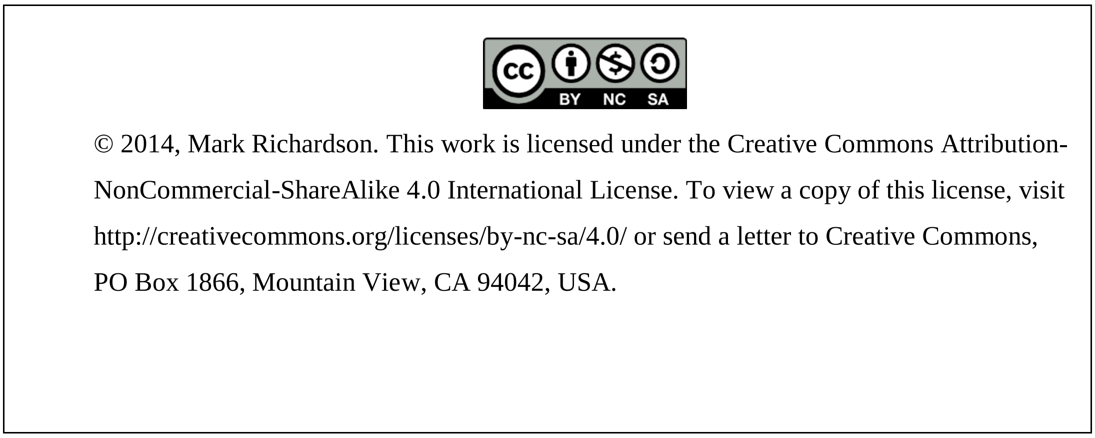

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Figure 2-3: Creative Commons Licencing

The above logo and text will be placed on the 'Limitations of Use' page at the front of this dissertation.

Chapter 3. – Enabling Technologies and Rapid Prototyping

The advent of new technologies has allowed society, including engineers, to develop devices like the DSD which have previously been either not technically achievable, or not viable due to costs. Technologies such as open source microprocessors, 3d printing technology, cheap sensors such as accelerometers, and mobile phone technology are all examples that have enabled devices such as the DSD to become viable by either costing less, or becoming technically achievable.

Haptic control of robots for under $200 (Ebay 2015), drones with high resolution cameras available at low cost, and mobile phones with the capabilities to monitor sleep patterns, GPS track, or control other devices through either wireless or Bluetooth technology.

These technologies have allowed the DSD to become a viable low cost device which can be replicated by anyone in the world who has access to a 3d printer, an Arduino, other basic components and the internet.

3.1 Enabling technologies

The literature review has demonstrated that there are no devices available which can dynamically control arm movements to ensure that people displaying SIB behaviour are prevented from harming themselves or others when required, while allowing freedom of movement at all other times.

Specific technologies that have enabled this project which would have rendered a low cost device unviable previously are;

- Rapid prototyping made available through low cost **3d printing equipment**
- Open Source microprocessors such as the **Arduino** which can be bought for under $20 with the capability to process analogue, digital and serial signals at fast processing speeds.
- Sensors such as **3 Axis Accelerometer**s for under $20 which can be integrated into microprocessors.

- Cheap user interfaces such as **LCD displays** (under $20) and **Mobile phones** which can easily interface with microprocessors via serial communications.
- **Online Community** of people using open source technologies which have enabled both accelerated advancement and online help for users who are helped by other users.

3.2 Rapid Prototyping

Rapid Prototyping includes a range of techniques which have enabled physical parts to be quickly fabricated using three-dimensional computer aided design data.

Stereo lithography (STL) is a de facto standard for additive manufacturing in which the three-dimensional print is built up layer by layer. This is commonly known as 3D printing and has allowed easy and cost effective manufacture of plastic parts at low cost.

The cost of 3D printing machines has decreased dramatically in the past 5 years and has now reached the point where a 3d printer can be bought for under $1000 (3D Printer Superstore 2015).

3.3 Changing Design – Build cycle

The onset of available cost effective 3D printers has allowed the design – build – evaluate cycle to be modified. Traditionally due to the high cost of manufacturing one off prototypes, the design phase of equipment is important to get right, as modifying the design can be expensive. With 3D printers, other than purchasing the printer, there are no setup costs, therefore the cost of changing the design and printing another part is inexpensive, as once the 3d design can be modified with the only cost being the cost of material.

3.4 Low cost Microprocessor

Low cost microprocessors such as Arduino's have allowed the hobbyist to be able to program a microprocessor which has on-board inputs and outputs on a single device. The Arduino Nano has 8 analogue inputs/outputs, 12 digital inputs/outputs, a programmable serial USART, a 20MHz processor and USB connectivity with on-board bootloader.

These devices have allowed flexible programming by allowing modifications to the code easily without the need for extra components. The only components required are to protect inputs, or if extra power is required for outputs. Once the inputs and outputs are designed, changes to the code can be made easily as required.

As with rapid prototyping, this flexibility in programming has allowed the design of code to be easily changed without modifying electronics. For example, basic code can be written and then evaluated early to prove theories and ensure that the initial design is possible. Once this basic design phase has been tested, either modifications or additions can be made and further testing completed.

Chapter 4. - Methodology

This chapter explains how the project is intended to be planned, including the identification off tasks, resources and the development of a timeline through to project completion.

The consequential effects are also discussed, including safety issues, sustainability and ethical issues.

Central to this project is the idea that the Dynamic Splint Device (DSD) must be affordable and available to anyone who would benefit from it.

4.1 Planned Tasks

4.1.1 Research

The research for the project will need to be across many topic areas;

- The technical side of the project needs to be researched to ensure that the wheel is not re-invented. Existing technologies will be required to be researched to ensure that the project is unique. The technologies used will also need to be researched, ensuring that the components chosen are the most suitable for the task.
- Information on self-injurious behaviour will be sought to ensure that the design of the project is as beneficial as it can be and to remove any assumptions made regarding the condition.
- The building of an adjustable splint mechanically is not the focus of this project, however is key to the success of making it work. Therefore research will be undertaken to determine the best way to make the splint.
- Laws and ethics are important factors with the design of a device that has the intention of restraining people. Therefore the laws and ethics of using a device like this are researched, as well as exploring how this device could change governmental policy.

- Since the project is to trying to prevent harm, the damage caused by impact is researched to try and determine the amount of force that causes harm so that it can be prevented.

4.1.2 Research/Theory

Research of the forces in the elbow will be completed and control theory used to control these forces via a braking mechanism and theory will be derived to determine the right components, including to;

- Determine braking force required to slow an arm down (to correctly size the braking mechanism).
- Determine the maximum velocity required to be detected (to purchase accelerometer)
- Determine actuation power required (to determine actuation voltage/current required to be generated and battery requirements)
- Apply control theory to control the arm velocity
- Determine the torques involved and consider using a strain gauge to determine the forces involved while the DSD is locked.

4.1.3 Design

A full risk review will be completed as part of the design phase to ensure that all safety, environmental and sustainability risks are addressed and mitigated where required.

The design phase will bring together the information from the literature review and the theory sections to begin deciding on how the DSD will be put together. Specifically;

- Design of mechanical joint utilising a 3d printer, with the 3D software code being integral to the design.
- Design the electronics to drive the braking mechanism.
- Design inputs to the electronics to determine arm speeds and forces.
- Design the functionality required.
- Design the control, using the inputs to control the braking mechanism.

- Design of an interface for a caregiver or health professional to control the DSD.

4.1.4 Build

The build phase will involve building to the design safely. Both the electronics and the mechanical device will be built and integrated. The build phase will revert back to a design phase wherever problems are encountered which needs redesign.

4.1.5 Evaluate

Evaluation will form each part of the build phase and at the completion of the build. The evaluation phases will be;

- Build DSD to test the strength of the brakes and confirm brake torque.
- Evaluate the sensors to ensure the readings are as expected.
- Evaluate the brake actuation to ensure the correct braking torque is applied when requested.
- Evaluate the control scheme against the design.
- Evaluate the comfort and safety of the DSD

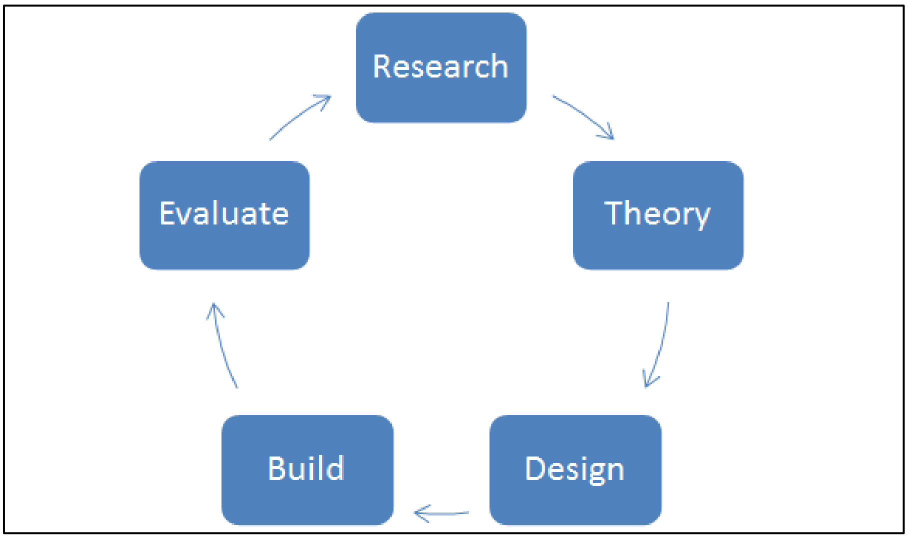


Figure 4-1: Project Cycle

4.2 Resource Requirements

Funds

This is a self-funded project with an extended budget of $5000. Below is a list of parts required, noting that the 3D printer and software are not solely for this project.

Table 4-1: Parts Funding

Parts	Price
3D printer	$1,600.00
Filament	$120.00
Electromagnetic Brake	$100.00
ERF Brake	$100.00
Arduino Uno	$30.00
Bluetooth electronics	$20.00
Accelerometer	$15.00
Miscellaneous parts	$100.00
High Density Foam	$40.00
Simplify3D Software	$150.00
Hardware	$50.00
Strain Gauges	$50.00
HX711 instrument amplifier	$20.00
Consumables	$100.00
Total	$2,495.00

Equipment

The equipment required to complete this project has already been purchased and no extra equipment is expected to be purchased. A list of equipment that will be utilised follows.

Table 4-2: Equipment Required

Equipment
3D printer
DC Regulated Power Supply
True RMS Multimeter
Temperature controlled Soldering Iron
Laptop Computer
Workshop with tools
Camera
Digital Oscilloscope

Purchasing Lead Times

Purchasing of parts has been identified as a potential issue. I have therefore identified all parts that are required and there lead times and purchased them upfront. At the writing of the preliminary report, the long lead time item equipment has been purchased and arrived. This included the electromagnetic brake and the 3D printer.

All other equipment purchased either has a short lead time, or can be purchased at extra cost with next day delivery from a local on line electronics store that has a large variety in in stock supplies (RS Components).

Facilities

A Private workshop has been utilised for the development of this project, which includes a full set of workshop tools and equipment. This workshop is accessible all hours, so will not be a limitation.

Software

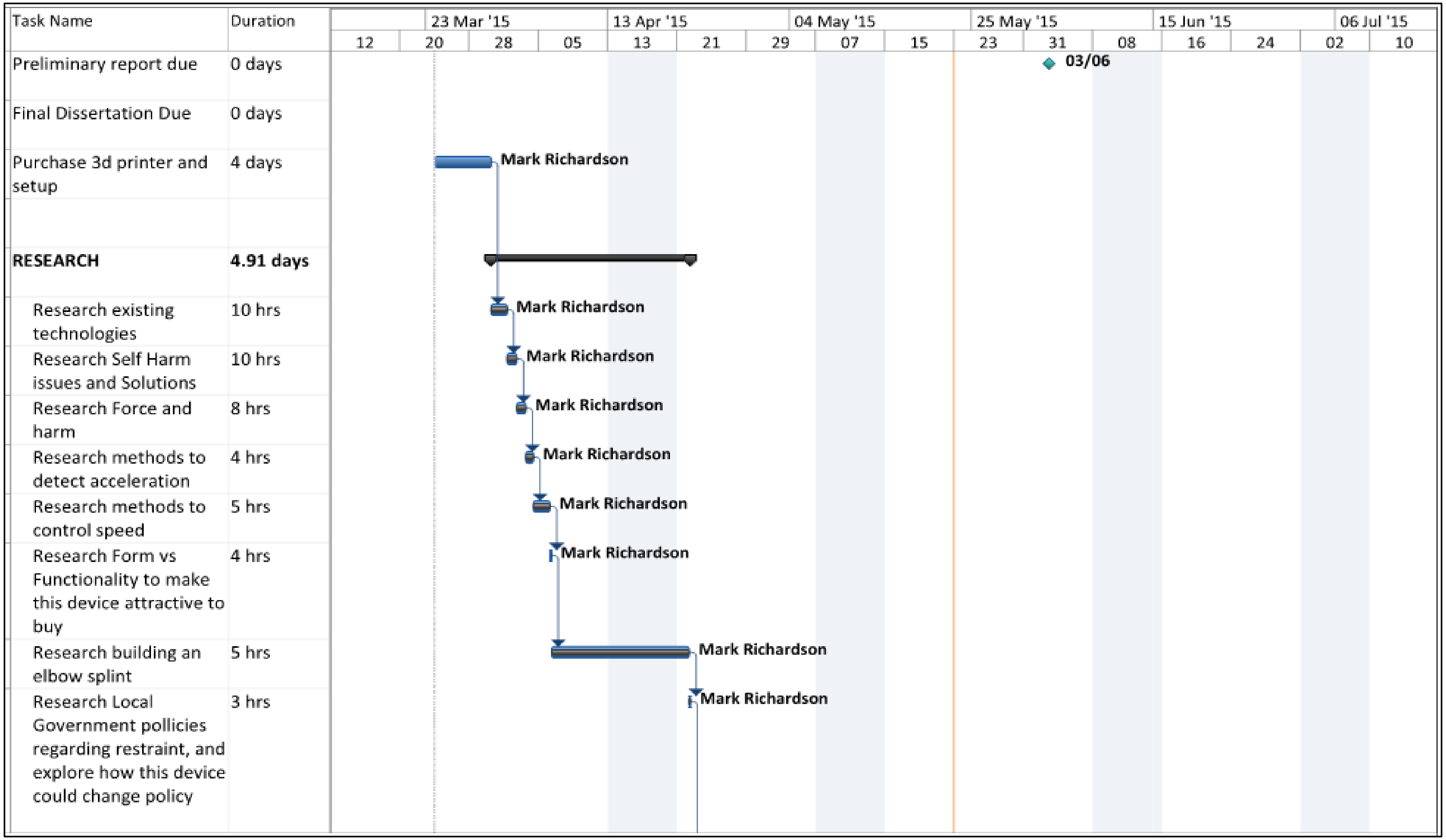
The software utilised for this project is either free software, or has already been purchased and therefore has not time constraints in obtaining the software.

The biggest resource requirement issue for the software is the time that it takes to learn new software packages. The software packages used include 3D printing software, oscilloscope software, Arduino software and Matlab.

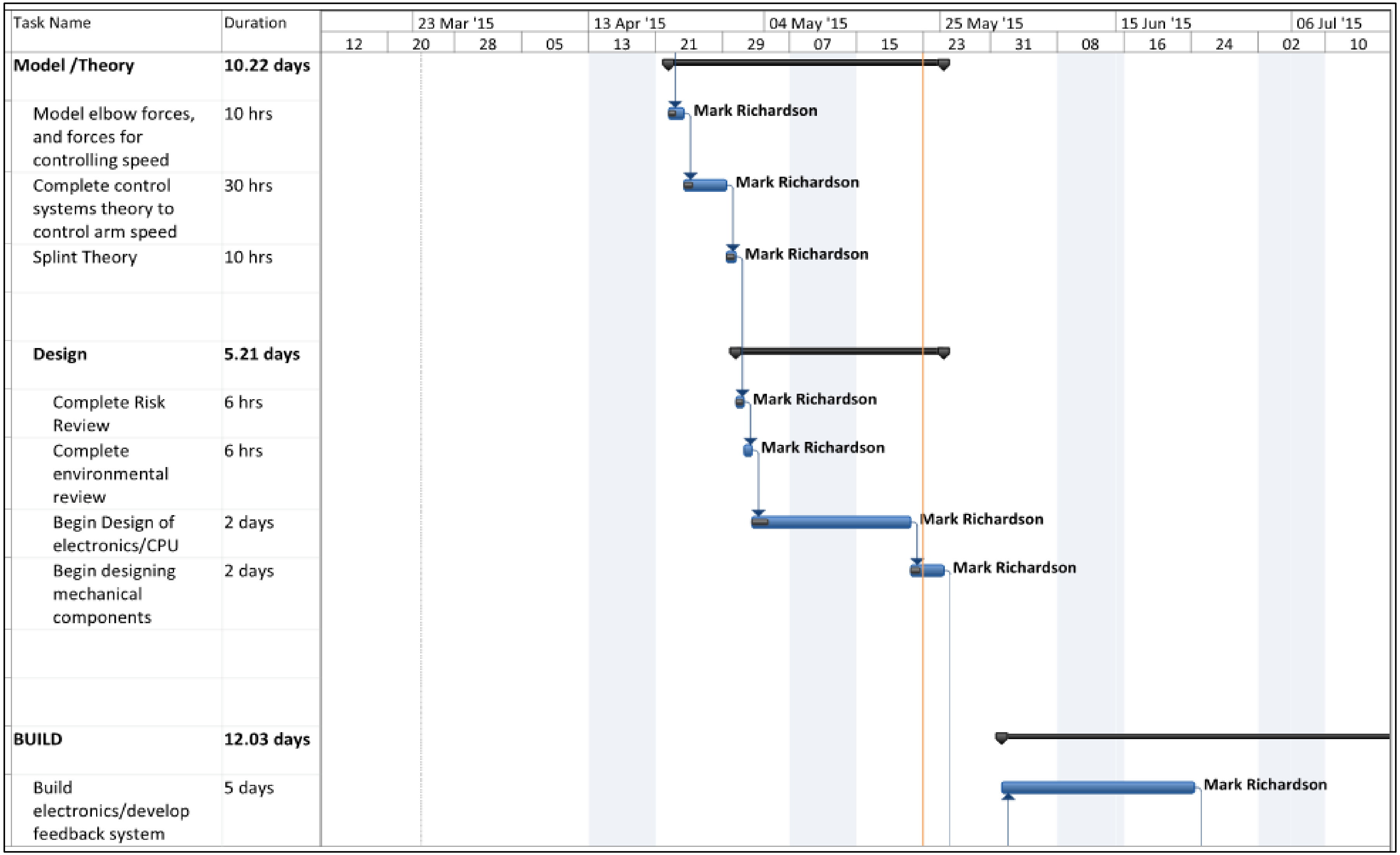
4.3 Timelines

A Gantt chart has been developed for this project and can be seen on the following pages.

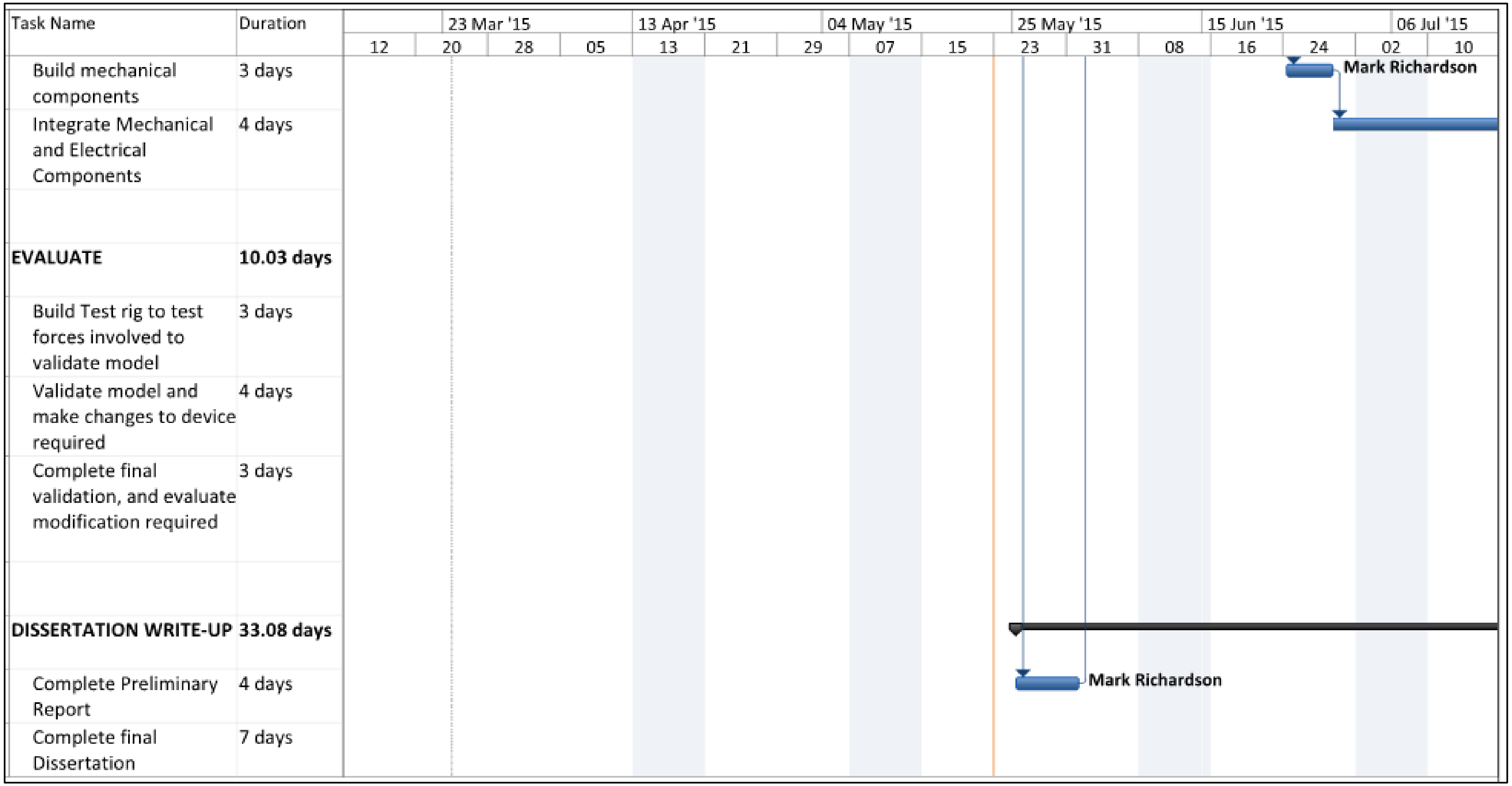
Table 4-3: Gantt Chart



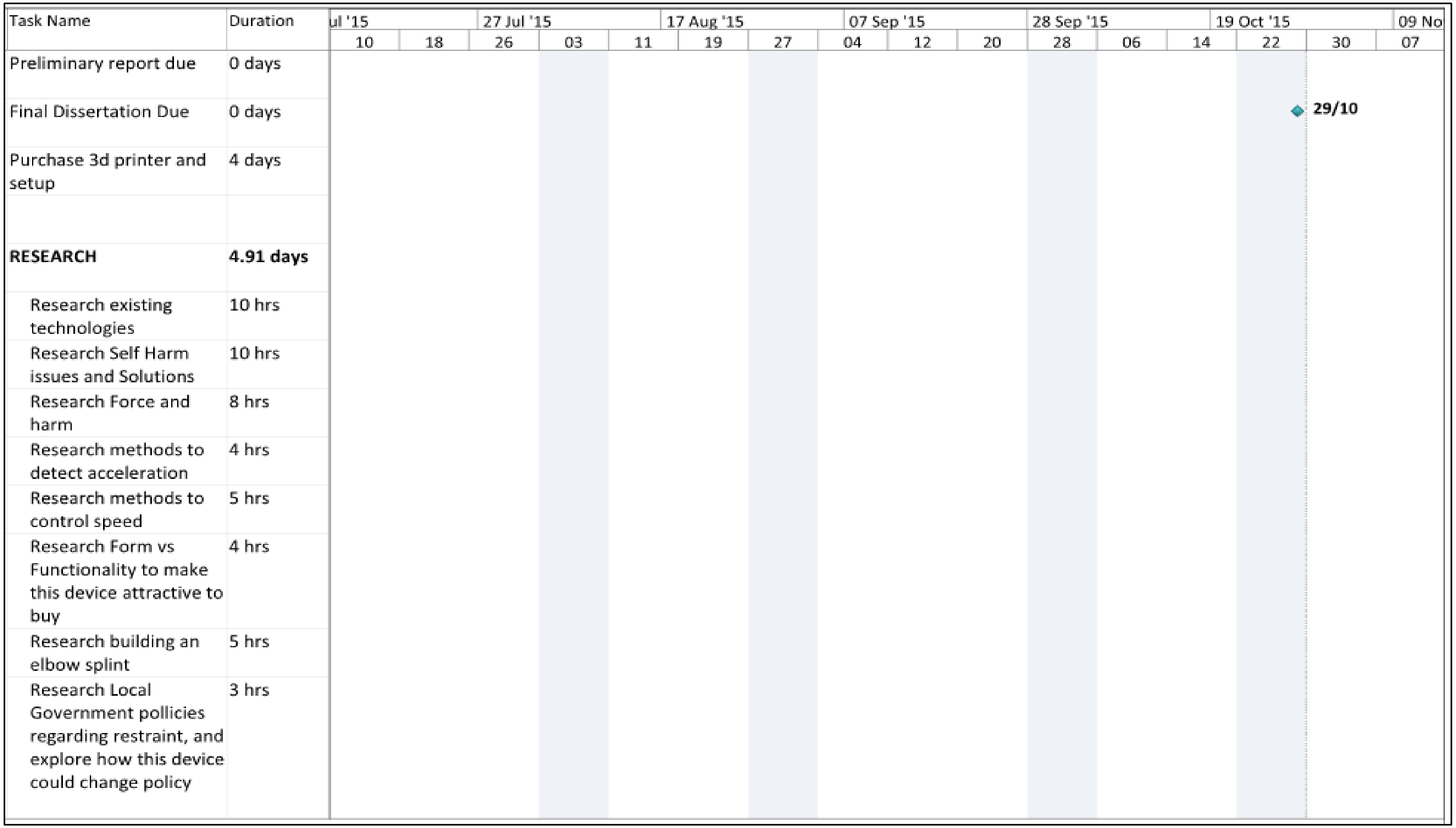
Task Name	Duration
Preliminary report due	0 days
Final Dissertation Due	0 days
Purchase 3d printer and setup	4 days
RESEARCH	**4.91 days**
Research existing technologies	10 hrs
Research Self Harm issues and Solutions	10 hrs
Research Force and harm	8 hrs
Research methods to detect acceleration	4 hrs
Research methods to control speed	5 hrs
Research Form vs Functionality to make this device attractive to buy	4 hrs
Research building an elbow splint	5 hrs
Research Local Government pollicies regarding restraint, and explore how this device could change policy	3 hrs



Task Name	Duration
Model /Theory	**10.22 days**
Model elbow forces, and forces for controlling speed	10 hrs
Complete control systems theory to control arm speed	30 hrs
Splint Theory	10 hrs
Design	**5.21 days**
Complete Risk Review	6 hrs
Complete environmental review	6 hrs
Begin Design of electronics/CPU	2 days
Begin designing mechanical components	2 days
BUILD	**12.03 days**
Build electronics/develop feedback system	5 days



Task Name	Duration
Build mechanical components	3 days
Integrate Mechanical and Electrical Components	4 days
EVALUATE	**10.03 days**
Build Test rig to test forces involved to validate model	3 days
Validate model and make changes to device required	4 days
Complete final validation, and evaluate modification required	3 days
DISSERTATION WRITE-UP	**33.08 days**
Complete Preliminary Report	4 days
Complete final Dissertation	7 days



Task Name	Duration
Preliminary report due	0 days
Final Dissertation Due	0 days
Purchase 3d printer and setup	4 days
RESEARCH	**4.91 days**
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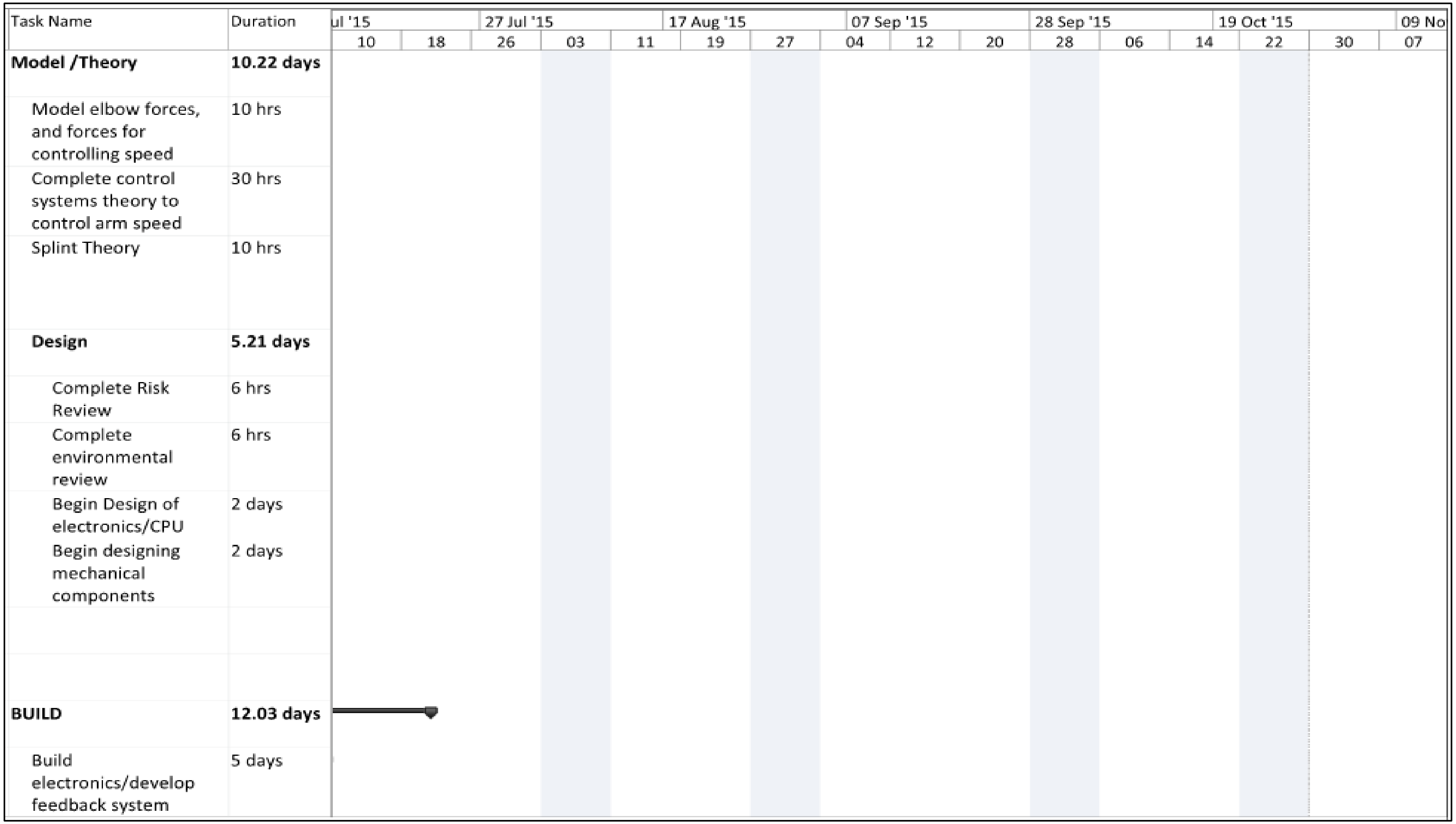

Task Name	Duration
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Complete environmental review	6 hrs
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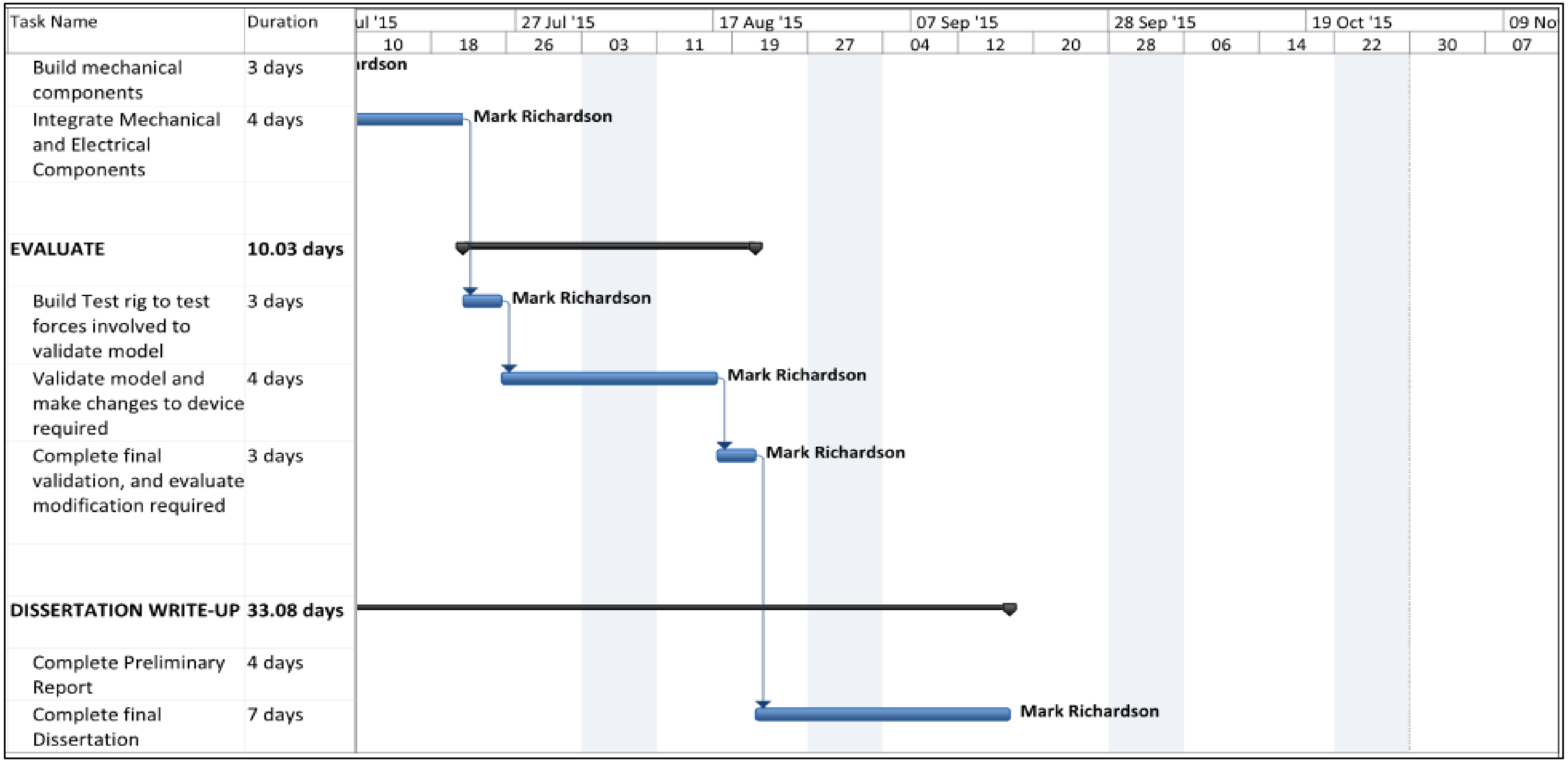
Build electronics/develop feedback system	5 days



Task Name	Duration
Build mechanical components	3 days
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EVALUATE	**10.03 days**
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Validate model and make changes to device required	4 days
Complete final validation, and evaluate modification required	3 days
DISSERTATION WRITE-UP	**33.08 days**
Complete Preliminary Report	4 days
Complete final Dissertation	7 days

4.4 Consequential effects

This project has potential consequential effects that have been identified. Issues involving safety, the environmental and ethics have been addressed.

Safety issues are addressed by the development of a risk matrix which has been developed from experience within industry and from this risk matrix a Job Hazard Analysis (JHA) has been developed to determine mitigations for hazardous tasks.

Environmental issues are addressed within the risk assessment.

There are also legal issues relating to the manufacture of this device. Legal issues surround the safety of the DSD and also the use of the DSD for restraint.

The ethics of placing a device that is designed to restrain someone against their will is complex. The following sections discuss an overview of the issues, along with the legalities and best practices within the health care industry.

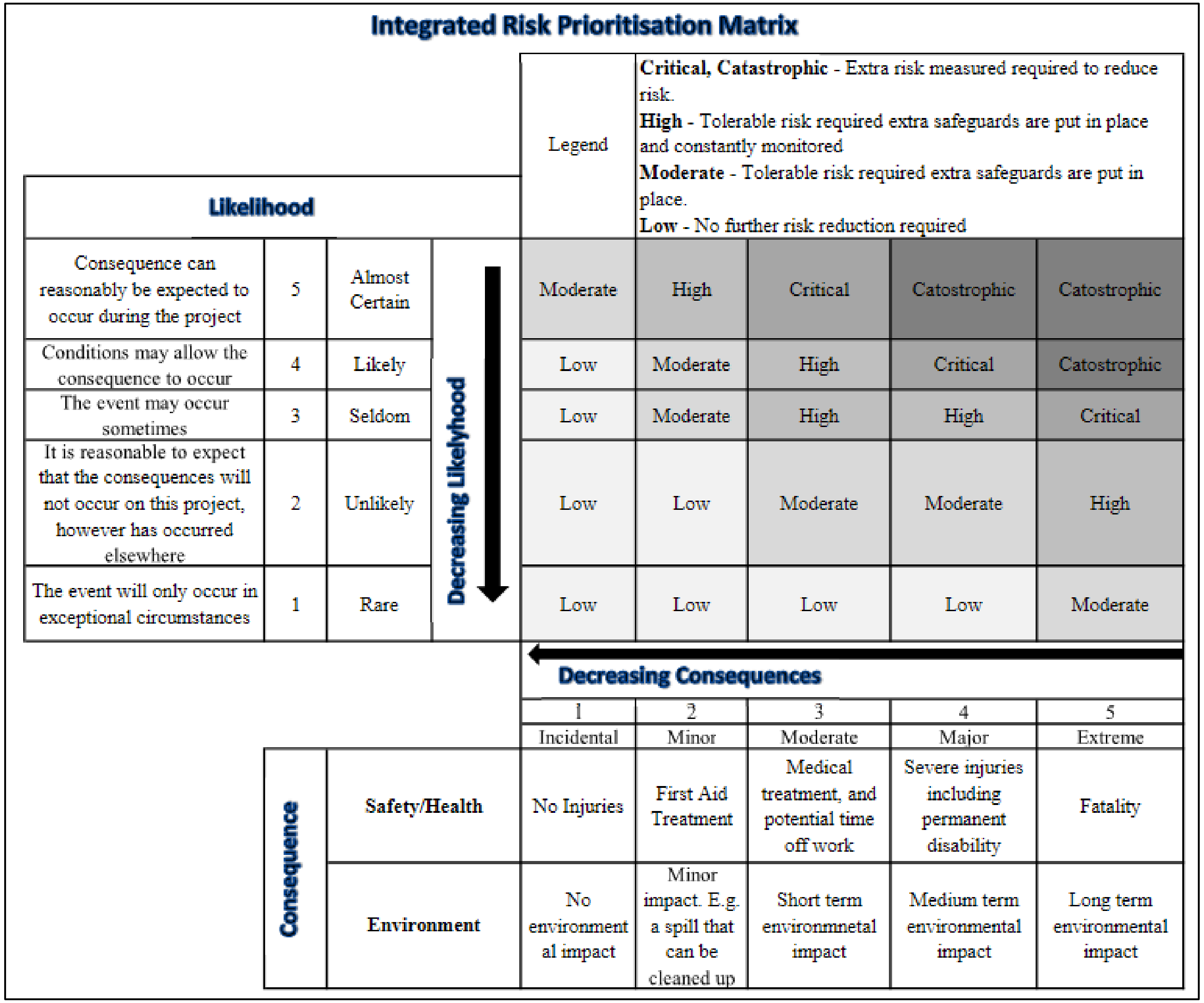
4.4.1 Safety Issues (analysis)

On the following page a risk matrix has been developed and applied to a hazard analysis. The risks reviewed are within the fabrication, testing and ongoing use phases.

The hazard analysis is task based and analyses the task initially with no controls in place and then mitigation is put in place, then a second risk assessment is completed with the mitigation in place to ensure that the risk is reduced to an acceptable level.

There is a risk that the DSD could be used other than intended and cause harm. This safety risk has been seen as low, since there are no parts that are driven, the DSD is seen to be no different to any hinged device. The risks associated with the device being used on people against their will are seen as an ethical issue and has been addressed in a later section.

Table 4-4: Risk Matrix



Integrated Risk Prioritisation Matrix

Legend

Critical, Catastrophic - Extra risk measured required to reduce risk.
High - Tolerable risk required extra safeguards are put in place and constantly monitored
Moderate - Tolerable risk required extra safeguards are put in place.
Low - No further risk reduction required

Likelihood								
Consequence can reasonably be expected to occur during the project	5	Almost Certain	Decreasing Likelyhood	Moderate	High	Critical	Catostrophic	Catostrophic
Conditions may allow the consequence to occur	4	Likely		Low	Moderate	High	Critical	Catostrophic
The event may occur sometimes	3	Seldom		Low	Moderate	High	High	Critical
It is reasonable to expect that the consequences will not occur on this project, however has occurred elsewhere	2	Unlikely		Low	Low	Moderate	Moderate	High
The event will only occur in exceptional circumstances	1	Rare		Low	Low	Low	Low	Moderate
				Decreasing Consequences				
				1	2	3	4	5
				Incidental	Minor	Moderate	Major	Extreme
	Consequence	Safety/Health		No Injuries	First Aid Treatment	Medical treatment, and potential time off work	Severe injuries including permanent disability	Fatality
		Environment		No environmental impact	Minor impact. E.g. a spill that can be cleaned up	Short term environmnetal impact	Medium term environmental impact	Long term environmental impact

Table 4-5: Hazard Analysis

Fabrication Hazard Analysis				
POSSIBLE HAZARD CATEGORIES: Gravity, Motion, Mechanical, Electrical, Temperature, Chemical, Radiation, Sound, Environmental				
Description of Task	**Hazard**	**Initial Risk Level**	**Control Measure to make job safer**	**Residual Risk Level**
Using Epoxy Glue	**Chemical:** Epoxy glue is a sensitiser and fumes may cause appropriate discomfort.	Moderate	Wear safety glasses with side shields, appropriate gloves and use in a well ventilated area. Ensure the MSDS is available and read.	Low
	Environment: Toxic to aquatic organisms	Moderate	Ensure leftover glue is disposed of in a safe way	Low
Working with 240VAC equipment	**Electrical:** 240VAC equipment poses an electrical risk	High	Ensure that 240VAC equipment is inspected by an electrician prior to use. Ensure that earth leakage circuit breakers are fitted and tested.	Low
Prolonged sitting at a computer	**Motion:** Prolonged sitting if not managed can cause strains	Moderate	Get up once per hour to stretch. Ensure that the height of the chair, monitor and keyboard are correct.	Low
Creating 3D Prints	**Temperature:** The temperature of the extruders can reach over 200 degrees and the bed temperature can be over 100 degrees	Moderate	Either wear high temperature gloves, or keep away from the hot extruder and bed when the machine is turned on	Low
	Chemical: ABS and PLA fumes may cause respiratory Irritation	Moderate	Use in well ventilated area. Read the MSDS available and read prior to use.	Low
	Chemical: Acetone dissolves ABS, so is used for creating ABS glue and for cleaning Vapours are highly flammable and can cause drowsiness. Skin contact may cause irritation and redness	Moderate	Use in well ventilated area. Avoid contact with skin. Read the MSDS available and read prior to use.	Low
	Environment: ABS and PLA are not toxic to the environment, however ABS will not degrade, where PLA is biodegradable.	Low	Ensure waste is kept to a minimum to reduce landfill. Re-use ABS where possible to create glues ny mixing with acetone.	Low
Using workshop tools and equipment	**Mechanical:** Workshop tools can cause impact injuries, eye injuries, cuts and abrasions	Moderate	Wear safety glasses with side shields, gloves appropriate to the task	Low
	Sound: Workshop tools can be noisy and long term exposure can cause permanent hearing loss	High	Ensure ear plugs are worn when completing noisy tasks	Low
Using workshop rotating equipment	**Motion:** Rotating equipment can cause swarf to become airborne, as well as the added risk of entanglement	High	Ensure safety glasses are worn, however DO NOT wear gloves when using rotating equipment due to the risk of getting the gloves caught in the rotating equipment. Secure all loose clothing, tie up loose hair and remove jewellery	Low

Testing Hazard Analysis

POSSIBLE HAZARD CATEGORIES: Gravity, Motion, Mechanical, Electrical, Temperature, Chemical, Radiation, Sound, Environmental

Description of Task	**Hazard**	**Initial Risk Level**	**Control Measure to make job safer**	**Residual Risk Level**
Working with 240VAC equipment	**Electrical:** 240VAC equipment poses an electrical risk	High	Ensure that 240VAC equipment is inspected by an electrician prior to use. Ensure that earth leakage circuit breakers are fitted and tested.	Low
Fit testing splint device	**Motion:** Pinch points in the splint	Moderate	Ensure that pinch points are designed out of the splint. Wear a long sleeved shirt, or place protective material over the arm prior to fitment	Low
	Mechanical: With the forces involved, the DSD can break and cause injury.	Moderate	Wear safety glasses with side shields and gloves. Inspect splint before and after every use for damage	Low

Ongoing Use Hazard Analysis

POSSIBLE HAZARD CATEGORIES: Gravity, Motion, Mechanical, Electrical, Temperature, Chemical, Radiation, Sound, Environmental

Description of Task	**Hazard**	**Initial Risk Level**	**Control Measure to make job safer**	**Residual Risk Level**
Fitting splint device	**Motion:** Pinch points in the splint	Moderate	Ensure that pinch points are designed out of the splint. Wear a long sleeved shirt, or place protective material over the arm prior to fitment	Low
Creating 3D Prints	**Temperature:** The temperature of the extruders can reach over 200 degrees and the bed temperature can be over 100 degrees and therefore can cause burns	Moderate	Either wear high temperature gloves, or keep away from the hot extruder and bed when the machine is turned on	Low
	Chemical: ABS and PLA fumes may cause respiratory Irritation	Moderate	Use in well ventilated area. Read the MSDS available and read prior to use.	Low
	Chemical: Acetone dissolves ABS, so is used for creating ABS glue and for cleaning Vapours are highly flammable and can cause drowsiness. Skin contact may cause irritation and redness	Moderate	Use in well ventilated area. Avoid contact with skin. Read the MSDS available and read prior to use.	Low
	Environment: ABS and PLA are not toxic to the environment, however ABS will not degrade, where PLA is biodegradable.	Low	Ensure waste is kept to a minimum to reduce landfill. Re-use ABS where possible to create glues ny mixing with acetone.	Low

4.4.2 Environmental Issues

Environmental issues are addressed in the hazard analysis above. The materials used are not harmful to the environment; but will contribute to landfill, however the design will be for the DSD to last and is therefore not a consumable item, so landfill contribution will be minimal.

The use of rechargeable batteries in the design will reduce the requirement for new batteries, and nickel metal hydride batteries are also chosen for environmental reasons (Ying et al. 2006).

4.4.3 Legal Issues

Under section 23 of the Work Health and Safety Act 2010 (Australian Commonwealth Government 2014), there is a duty of care to ensure that the DSD is without risks to the health and safety of people. This clause refers to businesses and is excluded for volunteer work, of which this is intended to be, however there is an intention to ensure that we abide by the act as best practice and ensure that the product is safe for use.

In 2014, a national standard for disabilities services was introduced into the Disability Services Act as the '*Disability Services Act (National Standards for Disability Services) Determination 2014'*. In schedule 1 of the these national standards (Australian Government 2014) it states that service strategies must be based on minimal restrictive options and are contemporary, evidence based, transparent and capable of review. To help service providers follow the new standard and national *Code of Practice for the Elimination of Restrictive Practices* (Commission, Disability Services 2014) has been developed and therefore should be used.

4.4.4 Ethical issues

The aim of the DSD is to better the life of people who are currently being treated with restraint devices to control challenging behaviour. Ethically, the values of this aim is sound, however there are still ethical issues surrounding the use of these devices at all.

Therefore the use of the DSD shall only be used on people, who have given full consent for the purposes of testing, or used by a health professional on a person as part of a holistic intervention program and approved by a treating team in consultation with the consent of a guardian. The health professional must also abide by the *Code of Practice for the Elimination of Restrictive Practices* (Commission, Disability Services 2014) which provides a framework to ensure that restrictive practices are a last resort. The use of restraint must also be approved by the service providers Positive Behaviour Support Panel and it must be proven that less restrictive practices have been evaluated and proven to not be applicable, or not to have worked.

In Western Australia where trials are likely to occur, permission to use a restraint device must be obtained through the Disabilities Services of Western Australia, sighted and records kept ensuring that all relevant laws and standards are complied with.

Chapter 5. – Design

This section describes the design process of the DSD. The requirements are first outlined and then each part of the DSD design is explored. The sections include;

- Determination of the maximum speed of the arm to minimise harm
- Calculation of braking power for a 10 N·m brake
- Calculations of speed to determine time required to activate braking
- Rationale for choosing components
- Development of the 'Electronic Ratchet' concept
- Design of the DSD interface
- Design of the Code
- Design of the output electronics to the electromagnetic brake
- Initial design of the 3D printed splint

5.1 Requirements

- *Safety.* As the device is intended to minimise harm, it is essential that the device does not cause any harm. The device also has to be perceived as safe by the carer.
- *Light with low mass/inertia.* The mass of the device must be kept to a minimum so as not to cause fatigue.
- *Comfort.* As the extended use of this device is probable, the device must be comfortable to wear and not cause fatigue in the wearer.
- *Ease of fitment.* The device must be easy to apply and remove from the carers perspective, however must be difficult to remove for the wearer.
- *DSD response speed.* The DSD must respond fast enough to impede any attempted impact.
- *Accurate speed sensing feedback.* The feedback needs to be accurate enough to ensure that the DSD can respond in time and accurately.
- *Reliability.* To gain user acceptance for this device, the device needs to be reliable, with minimum requirement for maintenance.

- *Simplicity.* The requirement of simplicity of this device is driven from reliability, a reduction in cost and ease of repair. If the device is kept simple then these other requirements should be easy to comply with.

5.2 Determination of Maximum Speed

This section determines the absolute maximum speed that the elbow joint should be limited to. This maximum speed will be derived from calculations of the maximum forces allowable to minimise harm to the wearer. The area of impact, mass of fist, velocity and acceleration of the punch, the amount the head moves, amount fist gives and the condition of the person are all factors that affect the impact energy transferred to the head. Some assumptions are required, as the mass, force, speed and duration of impact will be different for each individual and most of these parameters will be different with each impact attempted.

Assumptions made to allow for a conservative starting point for the calculations are:

- **Impact time is 10ms**. Previous studies have shown this to be the average contact duration for head impacts (Walilko, Viano & Bir 2005) and (Haddadin, Albu-Scha¨ffer & Hirzinger 2008)
- The **mass of the hand is 2kg**. The literature review determined that the effective mass of a boxers hand when punching was an average of 2.86 kg with a standard deviation of 2.03 kg (Walilko, Viano & Bir 2005). The effective mass used was2 kg. The decision was based on:
    - People with SIB would typically not be trained athletes
    - Punching would not use upper body rotation when self-inflicted
    - With a standard deviation of 2.03 kg, people with SIB could be expected to be at the lower end of the distribution.
    - Furthermore, the evaluation of effective hand mass will be different with each person and the accuracy of the calculations for the design of the DSD is not imperative, as the carers will have access to adjust the speed set-point to what is most effective.
- **Reduction of impact energy below 7 J** will not cause contusions (Geoffrey, Desmoulin & Anderson 2011).

- **0.66 kN force may break a cranial bone** (Haddadin, Albu-Scha¨ffer & Hirzinger 2008)**.**

Two methods were used to determine the maximum speed to reduce the harm to below acceptable levels. The first method uses the kinetic energy equation to reduce the available kinetic energy below 7 J to prevent contusions, while the second method uses the impulse momentum principle to reduce the force below 0.66 kN to prevent the breaking of any cranial bones.

5.2.1 Kinetic Energy Method

The equation for kinetic energy is;

$$J = \frac{1}{2} \times m \times v^2 \quad \textbf{(5-1)}$$

Re-arranging this equation determine the velocity from a mass and energy limit;

$$v = \sqrt{\frac{2J}{m}} \quad \textbf{(5-2)}$$

Therefore using the conservation of energy principles, with a mass of 2 kg and a force of 7 Joules;

$$v = \sqrt{\frac{14}{2}} = 2.646 m/s$$

Therefore if the velocity is limited to 2.646 m/s, the energy available will be limited to 7 J.

5.2.2 Impulse Momentum Method

The impulse momentum principle is used, which is derived from the Force equation;

$$F = m \times a \quad \textbf{(5-3)}$$

And since acceleration is the change in velocity;

$$F = m \times \frac{\Delta v}{\Delta t} \qquad \textbf{(5-4)}$$

Therefore re-arranging to form the impulse equation, which is

$$P = F \times \Delta t = m \times \Delta v \qquad \textbf{(5-5)}$$

Where P is the impulse in (N·s) and the change of momentum is in Kg·m/s.

Since the mass is constant and the change in velocity is from the velocity to zero velocity, the determination of the force for a given velocity is changed by the contact duration time. Therefore the velocity required to limit the force to 0.66 kN, with a fist weight of 2 kg and impulse time length of 10 ms is determined by first re-arranging equation 1-5 to solve for velocity;

$$\frac{F \times \Delta t}{m} = \Delta v \qquad \textbf{(5-6)}$$

Therefore;

$$\frac{0.66kN \times 0.01s}{2kg} = 3.3m/s$$

Therefore the velocity would need to be reduced to 3.3 m/s to limit the energy to 0.66 kN.

5.3 Determination of braking power

Braking power is required to reduce the force of the arm and therefore reducing the velocity and subsequent magnitude of impact. Ideally the braking power is to be greater than what can be produced by the arm. The aim was to find a brake with greater than 40 N·m force, which is the force that the average 26 year old young person can develop (Gallagher et al. 1997).

Research has revealed that the lightest brake available commercially is the electromagnet, or powder brake. Braking torques of around 40 N·m weigh in around 2 kg (Steki 2015), which is too heavy for a long term wearable device, especially when a splint, batteries and electronics are added to this weight.

Since 2 kg has been considered as too heavy to wear, practical consideration of the forces required was undertaken. A 10 N·m brake is available at a weight of 0.5 kg (Steki 2015). This 10 N·m was then converted to an equivalent weight being held in the hand and lifted by moving the elbow joint.

Therefore with Torque being equal to the Force multiplied by the distance;

$$\tau = F \times d \quad \textbf{(5-7)}$$

Therefore the Force is determined by;

$$F = \frac{\tau}{d}$$

Since the distance between the fist and elbow is 0.3 m on an average adult, then the mass required to cause 10 N·m is;

$$\frac{10Nm}{0.3m} = 33.33N$$

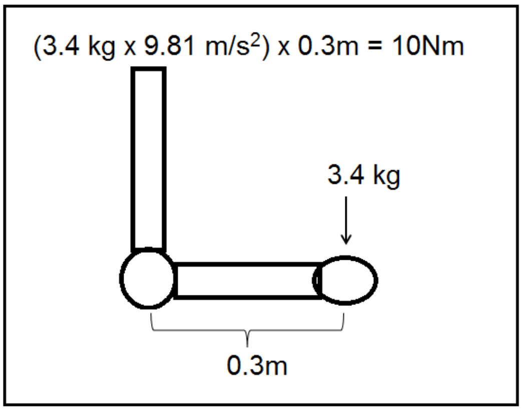


Figure 5-1: Braking power achieved with 10 Nm brake

Therefore 33.33 N which is equivalent to 3.4 kg, is the force that can be added instantaneously to the arm to reduce the speed, reducing the force available to cause injury.

5.3.1 Confirmation of braking power

The biomechanics of the arm is complex and not analogous to a simple torque rotating an arm, as the torque applied to the muscle is varying and often not sustained, while the opposing elements are also varying including the friction caused by opposing muscles, tendons, connective tissue and ligaments are also varying.

Due to the reduced braking torque available within an acceptable weight limit, further experimentation was completed to determine if the addition of a 10 N·m force to the elbow joint would reduce the speed. An electromagnetic brake was purchased which was capable of providing 10 N·m and strapped to the arm. The brake was then supplied with power (24 Volts DC) while attempting impact to the chest area.

This experiment showed that the even though 40 N·m can be generated, a 10 N·m braking force was sufficient to stop the movement. At 10 N·m the brake could be overcome. However, it was found that the maximum speed achievable was not enough to cause injury and the energy required to overcome this torque also fatigued the wearer.

This experiment showed that punching seemed to be a quick sudden release of energy rather than a sustained energy release and therefore the constant 10 N·m of energy release by the brake was sufficient to stop the arm.

5.4 Determination of Braking Speed Required

It is necessary to find the speed the arm can accelerate, so that the speed that a device will need to react to stop the acceleration of the arm can be determined. This is determined by calculating the moment of inertia to find the acceleration of the arm with an applied torque. Once the acceleration is known the time in which a certain velocity can be achieved can be determined.

5.4.1 Determination of angular acceleration

If the moment of inertia of the arm is simplified to a cylinder with the 2 kg weight evenly distributed along the arm, then the moment of inertia (I) equation is:

$$I = \frac{1}{3} m \cdot r^2 \quad \textbf{(5-8)}$$

Therefore; $I = \frac{1}{3} 2 \times 0.3^2$

$$I = 0.06.kg \cdot m^2$$

To determine the angular acceleration from torque and moment of inertia, Newton’s second law for rotation is used:

$$\tau = I \cdot \alpha \quad \textbf{(5-9)}$$

Therefore; $\alpha = \frac{\tau}{I}$

So a torque of 40 N·m applied to the elbow joint would accelerate the arm at;

$$\alpha = \frac{40.N \cdot m}{0.06.kg \cdot m^2} = \frac{40.kg \cdot m^2 / s^2}{0.06.kg \cdot m^2} =$$

$$\alpha = 667.radians / s^2$$

5.4.2 Determination of time to reach maximum speed of 3 m/s

The time to reach 3 m/s is then calculated by first converting 3 m/s to radians per second where;

$$\omega = \frac{v}{r} \quad \textbf{(5-10)}$$

$$\omega = \frac{3 m/s}{0.3 m} = 10.rad / s$$

Next to determine the time taken to reach the angular velocity of 10 rad/s. The equation for angular acceleration (α) is the change in angular velocity ($\Delta\omega$) over the change in time (Δt);

$$\alpha = \frac{\Delta\omega}{\Delta t} \quad \textbf{(5-11)}$$

Rearranging to determine the time taken to reach a given velocity;

$$\Delta t = \frac{\Delta\omega}{\alpha}$$

Assuming that the arm is at rest before the movement, then the time to accelerate to 10 rad/s is;

$$\Delta t = \frac{10 rad/s}{667 rad/s^2} = 0.015s$$

Therefore the time to reach 10 rad/s is 15 ms.

A final check is completed on the distance travelled while accelerating to this speed, which is calculated by the equation;

$$\theta = \frac{1}{2}\alpha \times t^2 \quad \textbf{(5-12)}$$

Therefore, the angular rotation achieved in 0.015 s under constant acceleration of 667 rad/s^2 using equation (5-12) is;

$$\theta = \frac{1}{2} 667 rad/s^2 \times 0.015s^2$$
$$\theta = 0.075.radians$$
$$\theta = 4.3°$$

5.4.3 Determination of time to reach the face from an arm open position

The time taken for the acceleration to reach the face is now determined. These calculations take into account the time from open to impact. The arm will not always be in the fully open position, however this is the worst case, as higher speeds are achievable from a further distance away.

The below figure shows the likely movement from extended to facial impact and shows that the angle is approximately 90 ° for impact. This was measured from a front punching position as well as a side punching position, 90 degrees was measured in each scenario.

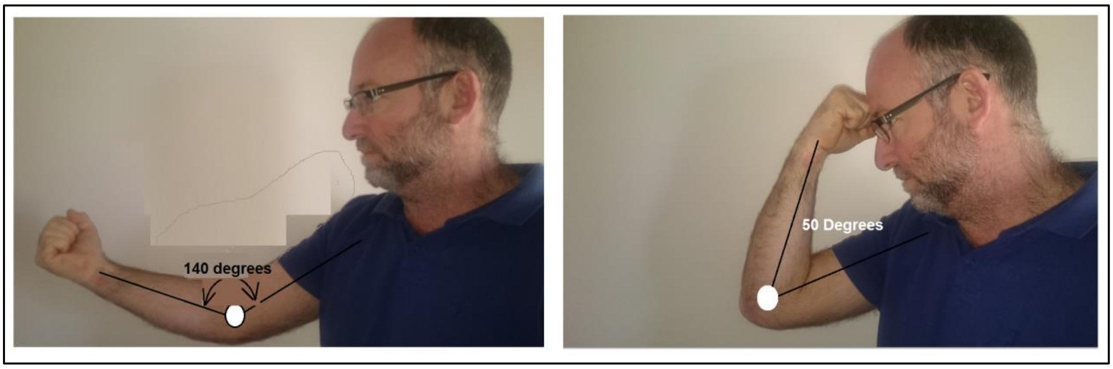


Figure 5-2: Front Impact Angle

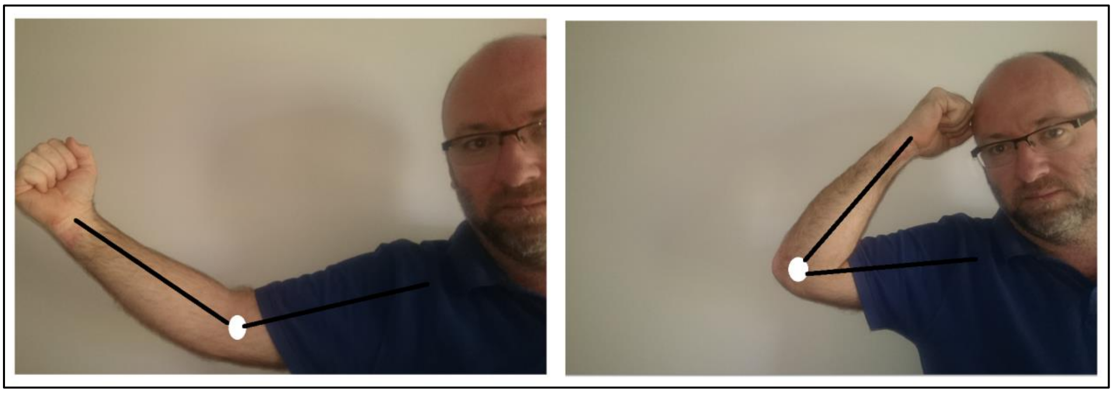


Figure 5-3: Side Impact Angle

Therefore, to determine the time of impact if the arm was to continue acceleration until 90 ° was achieved, we use a form of equation 5-12;

$$t = \sqrt{\frac{2\theta}{\alpha}}$$

$$t = \sqrt{\frac{\pi}{667}} = 0.069s$$

Therefore impact is achieved after 69 ms.

5.5 Specifications and Rationale for components

Following, are specifications and decisions made for the components of the DSD. The DSD is required to measure inputs to determine position and speed and control that speed via a braking mechanism.

5.5.1 Microprocessor

The microprocessor is required to;

- Scan at a speed faster than 0.015 s, in order to be able to apply an output before the velocity exceeds the maximum value of 3 m/s. NOTE that 0.005 ms is the minimum acceptable value of scan to ensure sufficient time to brake.
- Be able to brake at least 10 N·m, with an analogue style control
- Allow easy programming for modifications
- Allow serial communications to interface with external components
- Open source coding to allow users to modify as required
- Allow at least 4 analogue inputs, 1 analogue output and 6 digital input/outputs. This will allow for speed, position, acceleration and a spare analogue, as well as an analogue output for brake control and digital inputs and outputs for buttons and alarms.

The outcome of research completed favoured the Android family of microprocessors, however it needs to be determined if these processors are suitable. The Arduino investigated is the Arduino Nano. The Arduino Nano utilises the ATmega328 processor. This processor runs at 20 MHz, contains an on board oscillator, has 6 outputs which can be analogue via pulse width modulation and active power consumption at 0.2 mA (Atmel 2009). The ATmega328 on board the Arduino Nano has 12 inputs/outputs, 8 analogue inputs, serial communication and includes a bootloader to enable easy programming via USB.

The Arduino development environment is free and will run on any computer that supports Java. All that is required to start programming is a computer with a USB cable. The open source design of the Arduino allows modification, re-use of code and will allow a community of ‘Makers’ to modify the code to meet their own requirements. This will enable anyone to improve the design from anywhere around the globe, with the intent that the improvements can be incorporated into the design.

All of the requirements are met except for the processing speed which needs to be assessed. The ATmega328 has 20 MHz processing however the potential scan time needs to be determined.

Scan times are dependent upon the total amount of clock cycles and it is difficult to determine the final scan time. What can be found is the maximum amount of clock cycles and the average amount of code that would be allowed. Following are some facts and assumptions to determine of the ATmega328 is sufficient for the purposes of controlling the DSD;

- 20 million clock cycles occur every second.
- Most Instructions take between 1 and 3 clock cycles to execute, with an overage of 1.69 clock cycles, which we can round up to 2 clock cycles per second for this evaluation.
- At 2 clock cycles per instruction, 10 million instructions can be executed every second
- To ensure a 5 ms scan rate (200 Hz), 50,000 instructions can be executed within the code per scan if run at 10 MHz (10 MHz / 200 Hz).
- Allowing 200 lines of code, this allows an average of 250 instructions per line of code. Note that some lines of code will refer to library functions which add to this value.

These figures seem feasible. During development, the scan rate will need to be tested to ensure it is within 5 ms scan rate. This means that the device can react prior to reaching the maximum speed of 3 m/s and is fast enough to help arrest the arm before impact.

5.5.2 Position and Speed detection

To keep costs low, a potentiometer has been chosen to measure the position of the elbow joint. This enables both position and speed via calculation of the change of speed over time. The potentiometer is required to be mounted in the centre of the joint due to its rotating nature.

Acceleration can also be detected with the potentiometer by measuring the rate of change of speed. However, a decision was made to use an accelerometer to detect acceleration because, if an accelerometer is mounted close to the fist, then it could measure total acceleration rather than just the elbow acceleration.

5.5.3 Measurement of Acceleration

The requirement of the accelerometer is to measure acceleration in the arm to detect potential impact, as well as to detect if impact has occurred.

The accelerometer from an Android phone was used to get empirical data of rapid elbow flexion movements. The data is below;

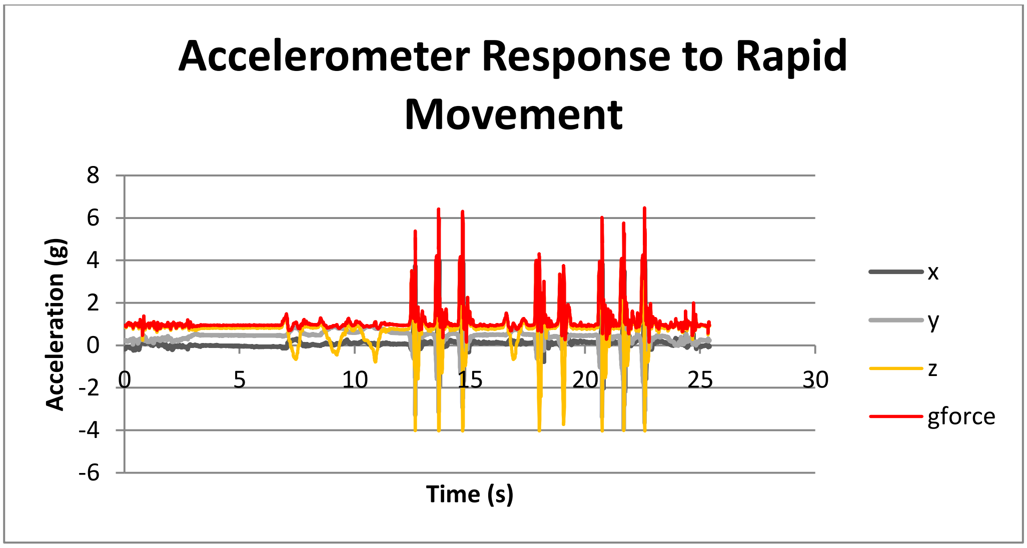


Figure 5-4: Android Accelerometer Response to Rapid Movement

This data shows that the acceleration of the arm reaches up to 6 g when the phone is held in the hand. Note that the individual sensors reached a force of around 4 g while the total acceleration is measured at 6 g. The total magnitude of acceleration was calculated by the equation;

$$|A_{Total}| = \sqrt{|A_x|^2 + |A_y|^2 + |A_z|^2} \quad \textbf{(5-13)}$$

The total magnitude measured of 6 g is greater than the magnitude required, as the data was collected with the phone held in the hand. The accelerometer position will not be mounted in the hand, but closer to the wrist where it will be convenient to mount. If the position of the accelerometer is 0.2 m from the elbow instead of 0.3 m where the fist is located, then the acceleration will also be reduced by the same amount. Therefore an accelerometer with a range of 6 g can measure an equivalent g-force of 9 g referred to the fist.

The accelerometer is to be used for two purposes;

- To record the amount of acceleration achieved to display to the carer
- To contribute to the speed control algorithm (derivative action)

5.6 Electronic Ratchet

While brainstorming the control of the DSD, a scenario was discovered which would allow harm to continue. If the arm was locked in a semi closed position, even though the elbow joint would be locked, the shoulder movement could still allow impact to take place, as seen in the below photo.

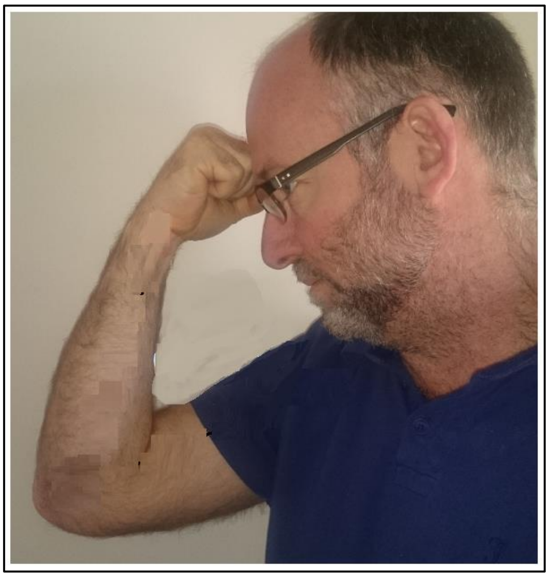


Figure 5-5: Punches permitted when locked in this position

To prevent this from occurring, it was seen as important to allow the arm to open when in this position, but not close again. Since motors have already been ruled out of the design due to weight, a method had to be devised which would allow this to happen. The solution to this problem is what will be referred to as the 'Electronic Ratchet'.

The Electronic Ratchet uses strain gauges embodied into the splint of the forearm. When the brake is applied, it will detect if the arm is trying to open, or close. Using the combination of the strain gauge and position sensor, the brake can be released when the arm is trying to open and applied again if the arm is moving towards the head.

Two strain gauges are to be installed with epoxy adhesive within the forearm piece, installed in a cantilever arrangement. The top strain gauge has a compressive strain ($-\varepsilon$) while the lower strain gauge has a tensile strain ($+\varepsilon$).

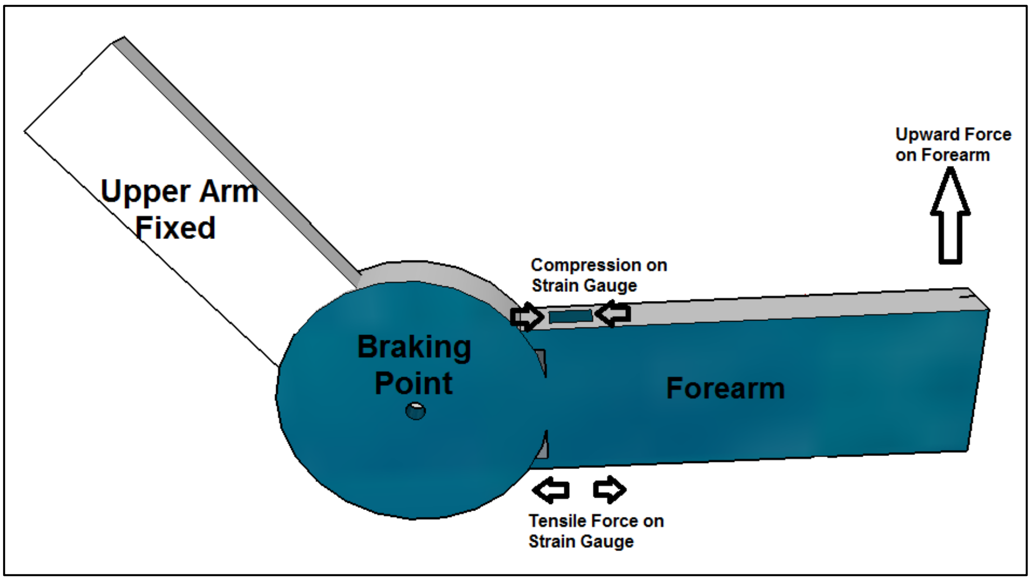


Figure 5-6: Strain Gauge forces

5.6.1 Analogue-to-Digital Conversion

The HX711 is a 24 bit Analogue to Digital (ADC) converter designed to be used directly with a Wheatstone bridge strain gauge arrangement (Avia Semiconductor 2014) and can be purchased for around $2 (ebay 2015). Reasons why the HX711 is suitable for this application include;

- It keep the design for the strain gauge amplification simple, as it is all contained on the chip
- Allows for flexibility in design since the HX711 is programmable
- Low cost

- Can be connected directly to an Arduino device without external circuitry.
- Readily available

HX711 has a programmable gain, a full-scale differential voltage of ± 20 mV or ± 40 mV depending upon the gain chosen and a digital serial output. An Arduino library also exists which is sourced from GITHUB (Bodge 2014). GITHUB is an online version control hub for software developers and also a place where open source code can be obtained from. This library function allows a calibration factor to be set, tares the device and controls the data signals to the HX711, which uses a software style serial communication to create a clock pulse on one digital pin and receive transmitted data on another digital pin.

The functions form the library to be utilised are;

- set_scale(LC_Cal_Factor): This command sets the gain of the scale to the value within the brackets.
- tare(): This command adjusts the offset to set the scale to zero.
- get_units(): This command gets the raw data from the HX711, applies the offset and scale factor by the equation

```
get_units = (read_average(times) - offset)/scale
```

The byte gain can be selected to 64, or 128. The gain was set to 128 to ensure that the module has high sensitivity. The gain can be reduced within the Arduino code if required.

A serial interface on board the chip provides a 24 bit output in 2’s complement. Only two data pins are required. One for the clock pulses (PD_SCK) and one for the serial output (DOUT). These pins are used for input selection, gain and data retrieval. The DOUT pin goes low when the module is ready for data retrieval.

The gain is set by the number of clock pulses set;

PD_SCK pulses	**Input Channel**	**Gain**
25	A	128
26	B	32
27	A	64

On each positive clock pulse, data is shifted out from the DOUT pin, starting with the most significant bit first until all 24 bits have been shifted out. Following the 24th bit the, the DOUT pin goes high and the number of following pulses on PD_SCK signify the gain used. This functionality is taken care of by the HX711 Arduino library function.

The full scale input range as per the HX711 datasheet (Avia Semiconductor 2014) is:

$$V = \pm 0.5\left(AVDD/GAIN\right) \qquad \textbf{(5-14)}$$

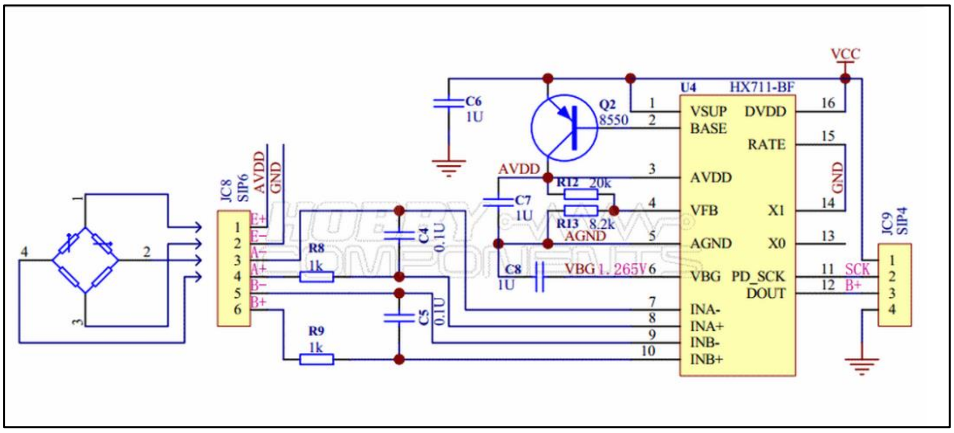


Figure 5-7: HX711 Circuit Diagram (Source: Hobby Components, 2013)

The above figure (Hobby Components 2013) shows the circuit that is supplied on the HX711 module.

5.6.2 Design of strain gauge circuit:

The most common strain gauge values commercially available are 120 Ω and 350 Ω. The 120 Ω strain gauge was chosen to complete design calculations with, because they are readily available and are also a common resistor value which can be used to balance the bridge.

A 120 Ω strain gauge was found from the RS ONLINE website (RS-Online 2015). The strain gauge has the following specifications;

• Gauge Length	5 mm
• Gauge Factor	2.1
• Gauge Resistance	120 Ω
• Length	9.5 mm
• Width	3.5 mm

To measure the strain of the forearm piece as per Figure 5-8, a half Wheatstone bridge with two active strain gauges on opposite sides of the forearm piece is used. When one strain gauge is in compression, the other is in tension and visa-versa. This amplifies the voltage difference, as well as opposing axial forces.

The resisters and strain gauges form two parallel voltage divider circuits as follows, where;

- ε = Strain. (Change in length divided by the original length)
- σ = Stress (Force divided by Area)
- R_g = Strain Gauge Resistance (R3 and R4)
- V_{EX} = Excitation Voltage (Measured between E+ and E-)
- V_{CH} = Measured Signal Voltage (Between A+ and A-)
- E = Stress (σ) divided by the strain (ε)
- GF = Gauge Factor (Fractional change in resistance, divided by the strain)

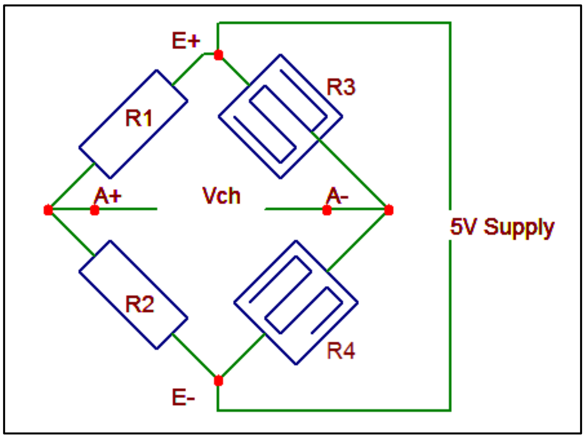


Figure 5-8: Half Wheatstone Bridge Arrangement

The Wheatstone bridge forms two voltage dividers, one with the resisters R1 and R2 (A+) and one with the two strain gauges R3 and R4 (A-). The equations for A_ and A- are therefore;

$$A+ = V_{EX}\frac{R2}{R1+R2} \tag{5-15}$$

$$A- = V_{EX}\frac{R4}{R3+R4} \tag{5-16}$$

Since the measured signal voltage is the difference between A= and A-;

$$V_{CH} = A+ - A- \quad \text{(5-17)}$$

Due to R1 and R2 being fixed resisters, A+ should always be;

$$A+ = V_{EX}\,\frac{1}{2} \quad \text{(5-18)}$$

Also, with the assumption that the tensile and compressive forces are the same magnitude, then $A-$ equation is

$$A- = V_{EX}\,\frac{R_0 - \Delta R}{2R_0} \quad \text{(5-19)}$$

Therefore combining equations (5-20) and (5-21), the measured signal voltage will be;

$$V_{CH} = V_{EX}\left(\frac{1}{2} - \frac{R_0 - \Delta R}{2R_0}\right) \quad \text{(5-20)}$$

5.6.2.1 Calculation of strain

The magnitude of strain is given by the following equation (Bentley 2005);

$$\varepsilon = \frac{6(l - x)}{w \cdot t^2 \cdot E}F \quad \text{(5-21)}$$

Where $l, w, and.t$ are shown in the diagram below and x is the distance to the strain gauge from the pivot point;

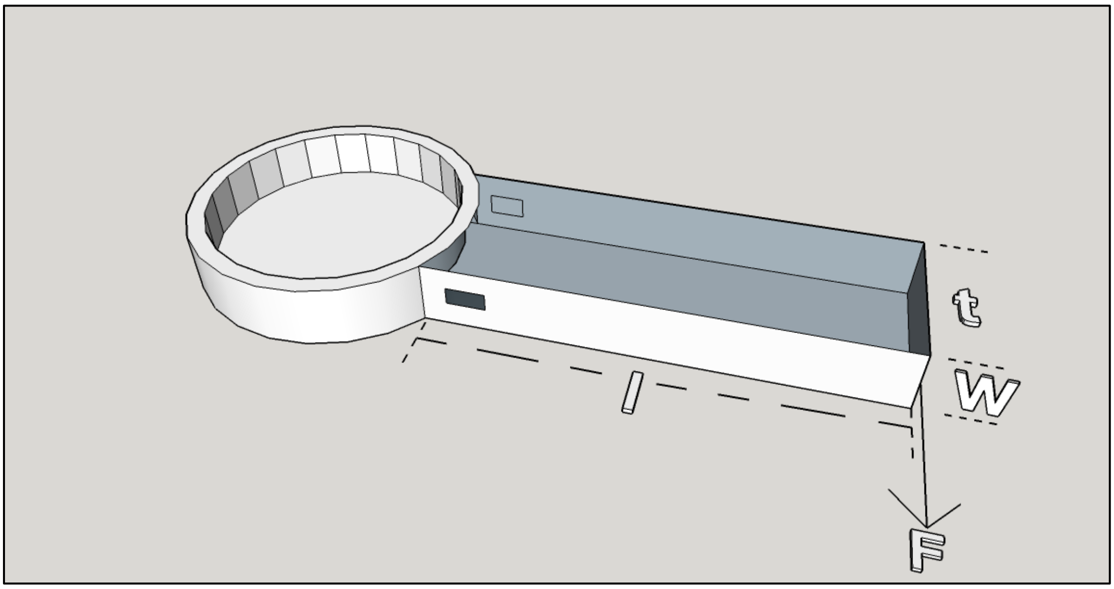


Figure 5-9: 3d Printed Forearm Dimension Labels

The Elastic Modulus (E) of PLA plastic printed from a 3d printer is 3368 MPa (B.M. Tymrak 2014). With a force of 40 N·m (Gupta & O'Malley 2008) being the maximum force, the following is an estimation of the build size:

l	=	200 mm
x	=	60 mm
w	=	15 mm
t	=	35 mm

$$\varepsilon_{MAX} = \frac{6(0.2m - 0.06m)}{0.015m \times 0.035m^2 \times 3368M\ N/m^2} 40Nm$$

$$\varepsilon_{MAX} = 543 \times 10^{-6}$$

5.6.2.2 Calculating Change in Resistance and Voltage

The expected change in resistance is calculated as follows:

The calculation for strain is:

$$GF = \frac{\Delta R}{R_0 \cdot \varepsilon} = 2.1$$ **(National Instruments 2014)....................................... (5-22)**

Re-arranging equation (5-24) gives

$$\Delta R = GF \cdot \varepsilon \cdot R_0 \quad \text{(5-23)}$$

Substituting known values gives the result;

$$\Delta R = 0.136\Omega$$

To calculate the voltage, ΔR is substituted back into equation (1-20);

$$V_{CH\_MAX} = 5\left(\frac{1}{2} - \frac{120 - 0.136}{240}\right)$$
$$V_{CH\_MAX} = 2.83mV$$

To keep within the limits of the HX711, the next calculation determines the maximum gain to amplify this 2.8 mV to the maximum of the HX711. The HX711 datasheet (Avia Semiconductor 2014) states the full scale differential input range as;

$$\left(A^+ - A^-\right)_{MAX} = 0.5\left(\frac{V_{SUPPLY}}{GAIN}\right) \quad \text{(5-24)}$$

Therefore the maximum gain is determined to be

$$GAIN_{MAX} = 0.5\left(\frac{5V}{\pm 2.83mV}\right)$$

$$GAIN_{MAX} = 883$$

Therefore, any gain below 883 will not exceed the requirements of the HX711.

Using the same equation (1-26) and re-arranging to determine the mV range from a gain of 128:

$$V_{MAX} = \pm 0.5\left(\frac{5V}{GAIN}\right)$$
$$V_{MAX} = \pm 19.53mV$$

5.6.2.3 Calculated digital value range from HX711

Since the HX711 outputs a 2’s compliment number, the maximum max of 2^{23} (one bit for the negative) is 8,388,608.

Since 40 N·m gives a voltage of 2.83 mV, the sensitivity becomes;

$$\frac{40Nm}{2.83mV} = 14.13Nm/mV \qquad \textbf{(5-25)}$$

To equate this to a digital value from the 24 bit HX711;

The data value per mV is;

$$\frac{2^{23}}{40mV} = 209705/mV \qquad \textbf{(5-26)}$$

Finally, to determine the data value per Nm, equation (5-28) is divided by equation (5-27)

$$\frac{209705}{14.13} = 14841/Nm$$

This value will be used as the calibration factor in the Arduino. Note that the value will be determined empirically. The value is not expected to be exact due to variability in the young's modulus, differences in the 3D print and differences in the strain gauge GF.

5.7 Interface

A requirement to interface with the DSD was identified to;

- Adjust the speed set-point depending upon situation
- Turn the device on/off
- Apply the brake manually if required
- Calibrate the sensors (tare the strain gauge and calibrate the accelerometer)
- Turn the ratchet mode on or off

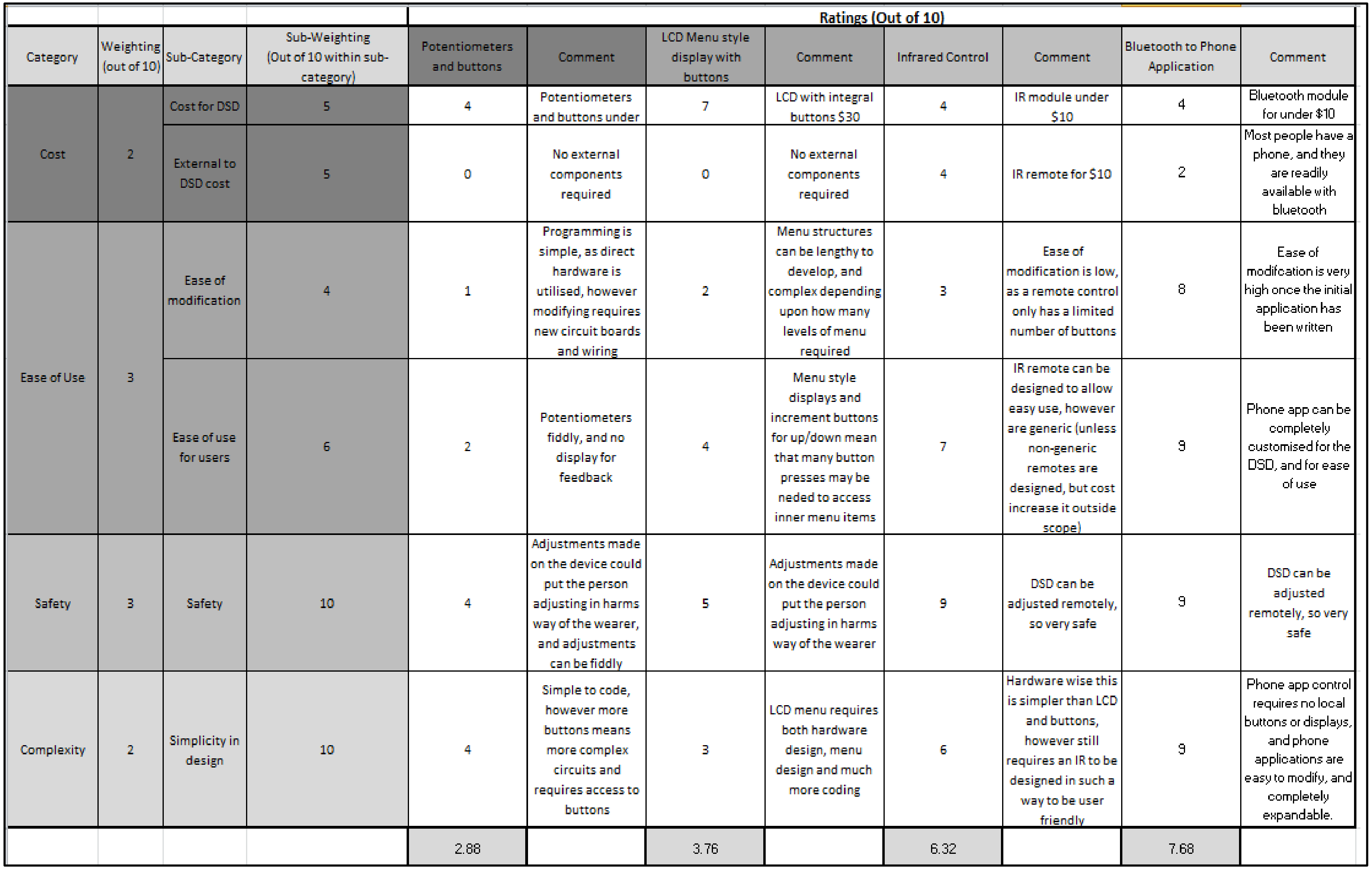
Different methods of interfacing considered were

- Local potentiometers to adjust settings and switches to adjust modes,
- LCD display with local buttons, with a menu style approach for adjusting settings

- Infrared Remote control
- Android application with Bluetooth connectivity

Advantages and disadvantages of each option were considered. The cost, ease of use, safety and simplicity were all weighted. The best option is the Android application with Bluetooth connectivity, because the only hardware required is a Bluetooth module, the phone application is customisable and can be modified without any additional hardware.

Table 5-1: Interface Display Decision Matrix



				Ratings (Out of 10)							
Category	Weighting (out of 10)	Sub-Category	Sub-Weighting (Out of 10 within sub-category)	Potentiometers and buttons	Comment	LCD Menu style display with buttons	Comment	Infrared Control	Comment	Bluetooth to Phone Application	Comment
Cost	2	Cost for DSD	5	4	Potentiometers and buttons under	7	LCD with integral buttons $30	4	IR module under $10	4	Bluetooth module for under $10
		External to DSD cost	5	0	No external components required	0	No external components required	4	IR remote for $10	2	Most people have a phone, and they are readily available with bluetooth
Ease of Use	3	Ease of modification	4	1	Programming is simple, as direct hardware is utilised, however modifying requires new circuit boards and wiring	2	Menu structures can be lengthy to develop, and complex depending upon how many levels of menu required	3	Ease of modification is low, as a remote control only has a limited number of buttons	8	Ease of modifcation is very high once the initial application has been written
		Ease of use for users	6	2	Potentiometers fiddly, and no display for feedback	4	Menu style displays and increment buttons for up/down mean that many button presses may be neded to access inner menu items	7	IR remote can be designed to allow easy use, however are generic (unless non-generic remotes are designed, but cost increase it outside scope)	9	Phone app can be completely customised for the DSD, and for ease of use
Safety	3	Safety	10	4	Adjustments made on the device could put the person adjusting in harms way of the wearer, and adjustments can be fiddly	5	Adjustments made on the device could put the person adjusting in harms way of the wearer	9	DSD can be adjusted remotely, so very safe	9	DSD can be adjusted remotely, so very safe
Complexity	2	Simplicity in design	10	4	Simple to code, however more buttons means more complex circuits and requires access to buttons	3	LCD menu requires both hardware design, menu design and much more coding	6	Hardware wise this is simpler than LCD and buttons, however still requires an IR to be designed in such a way to be user friendly	9	Phone app control requires no local buttons or displays, and phone applications are easy to modify, and completely expandable.
				2.88		3.76		6.32		7.68	

5.7.1 Changing design

The above matrix table shows the basis for the final decision. The interface went through a fluid design process in the early stages of development. The interface was initially the Arduino environment’s built in serial monitor to both read and write values. This allowed early coding to take place prior to fully developing the permanent interface.

The next stage was the design of an LCD. The advantages of the LCD include that interfacing to the DSD can be done without the need to connect to a computer, not spending project time learning how to create a phone application, and it gives a simple user interface to complete most tasks. Disadvantages include the requirement to scroll through menu items to get to the setting required, and the inflexibility of being limited to 2 lines of display.

The decision to create a phone application was late in development and a difficult decision. This project attempts to prove the concept that an electronic device can stop people with SIB harming themselves. The addition of creating a phone application does not help prove the concept of the hardware, however following the completion of this dissertation, the DSD is intended to be further refined for use in society. Therefore, a phone application made the device safer and more user friendly. The phone application also enables the design to be easily changed, adds the advantage of modern phone colour touchscreens and also significantly reduces the cost and size of the electronic component of the DSD.

5.7.2 LCD Design

The LCD was connected to the Arduino and allowed access to menu style options which the user can change settings with. The display was organised with the following menu:

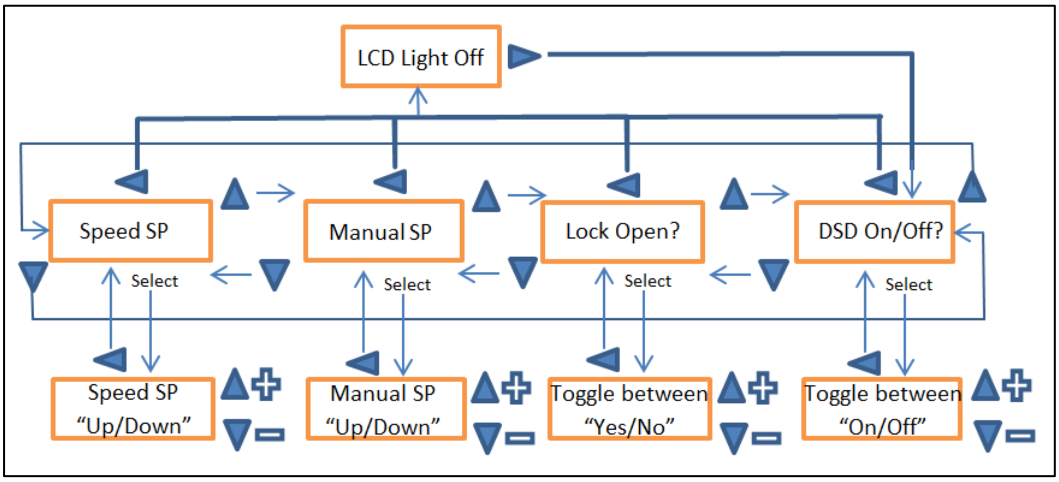


Figure 5-10: LCD Menu Structure

The LCD light off saves power and forms the start of the menu. Once the ► button is pressed, the menu went to the upper menu of "DSD on/off?". From here, the ▲ or ▼ buttons will scroll between settings, the 'Select' button will enter the sub-menu for the setting and the ◄ button will return to the main menu. If there is inactivity for longer than 10 seconds, then the light will automatically be turned off.

The calibration of the accelerometer is completed by pressing the ► button while in the upper main menu.

The Arduino code which drives the LCD display can be seen in Appendix D.

5.7.3 Phone Graphics

To develop the graphics, the functions and interfaces required were first listed. The main requirement is to be able to request the DSD to:

- Brake immediately when required
- Put into speed control mode and request a set-point from 0 % to 100 %
- Put into manual control mode to adjust the brake output from 0 % to 100 %
- Turn the ratchet mode on and off

Secondary requirements of the DSD are to

- Calibrate the accelerometer
- Calibrate the strain gauge

- Display the maximum speed and force
- Reset the maximum speed and force
- Display the current strain
- Display clearly what mode the DSD is in

Graphics were developed to meet these requirements. Buttons which cannot be pressed in the current mode are either greyed out or not made visible. Below is a figure of the screen layout, with all buttons showing. Each button has a name which is shown in brackets (to be used in the coding) and the horizontal lines indicate horizontal groups of components with the horizontal label indicated to the right hand side.

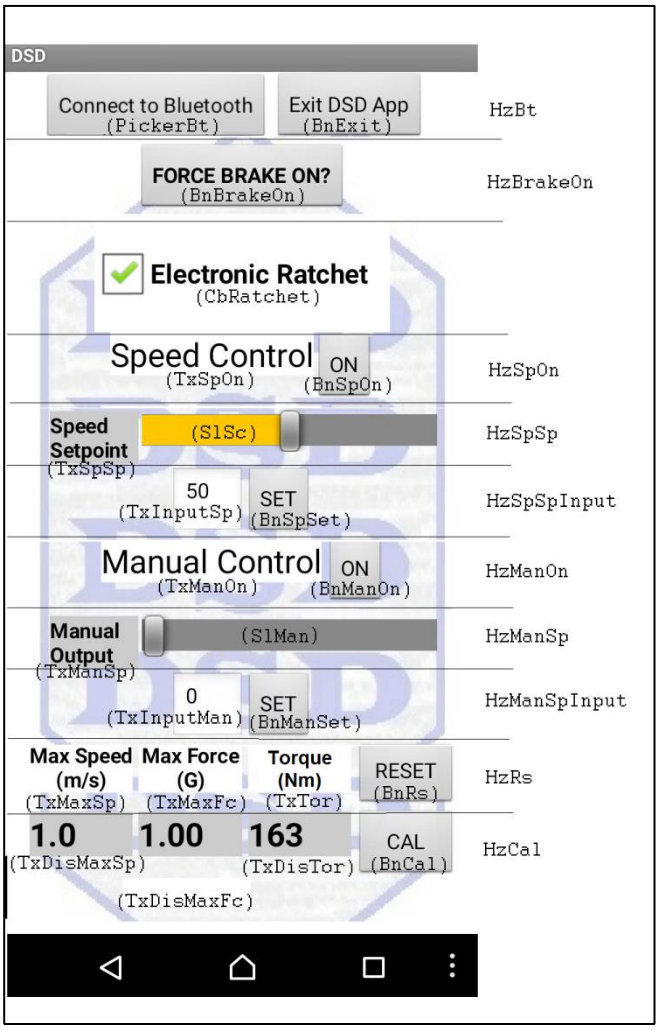


Figure 5-11: Phone Application Layout

To ensure that only relevant information is displayed to the user, the following rules were used for the display of graphics:

Specific Rules

Until Bluetooth connected:

- Only display the ‘Connect to Bluetooth’ and ‘Exit DSD App’ buttons.

Once Bluetooth Connected Screen;

- Remove the ‘Connect to Bluetooth’ button

When Speed Control is off

- Do not display the Slider or text box input display related to the speed control

When Manual Control is off

- Do not display the slider or text box input display related to the Manual control

When the Speed Control is on;

- Hide the manual control slider and text input controls.

When Manual Control is on;

- Hide the Speed Control slider and text input controls.

When the ‘Force Brake On?’ button is pressed;

- Hide the manual and speed control input controls
- Grey out the manual and speed control on/off buttons

Generic Rules

- Rather than display on and off buttons separately, change the text of the buttons depending upon the state. For example, change an ‘ON’ to an ‘OFF’ when the button has been switched on.
- When the ‘FORCE BRAKE ON?’ button has been activated, change the background to a red and yellow symbol to signify that braking is in place.

5.8 Arduino Code Design

The Arduino code is where most of the processing takes place. The code is broken up into sections that complete the following tasks;

- Initial setup of variables, communications and sensors
- Accept analogue and digital data from the phone’s Bluetooth serial connection
- Send sensor data and status to the phone for display
- Allow calibration of sensors
- Use accelerometer, strain gauges and position sensor to calculate position, speed, acceleration
- Process sensors data for PID control of the brake
- Output an analogue output to the brake unit

See Appendix D for a full listing of the code.

5.8.1 Initial Setup

The initial setup of the Arduino needs to take into consideration the inclusion of libraries, variable declarations and the ‘setup()’ function which is the first code to be executed.

There are two libraries used. One for the HX711 strain gauge amplifier (Bodge 2014), and another for the MMA7361 Accelerometer (jeroendoggen 2012). These libraries allow for standard library functions to be used.

Data types declared include Boolean, Character, integer, Long and Floating. The full list can be seen in Appendix D.

The setup function must complete the following tasks:

- Begin the serial communications
- Set up the accelerometer chip (via library commands)
- Set the mode of the digital pins
- Call the main function

5.8.2 Phone requests

The Bluetooth adapter used is a HC-06 Bluetooth to UART serial wireless adaptor which can be obtained for under $10. The BAUD rate is 9600 bps and the HC-06 connects directly to the hardware serial connection on pins 0 (receive) and 1 (transmit). The default is used with 8 data bits, no parity and one stop bit.

The code to setup communications to receive serial data from the Bluetooth module is:

```
Serial.begin(9600);
```

If the serial is available to read, then the characters are stored into the “recd_data” variable.

5.8.2.1 Analogue Signals from Phone

Two analogue values are sent from the phone to the DSD. Speed set-point and Manual output set-point. To differentiate between the two, a leading character is sent prior to the analogue and a trailing ‘/’ is sent to indicate the end of the analogue value.

The analogue values sent from the phone are characters, conversion from ASCII to decimal is required. This is achieved by subtracting the character ‘0’ from the receiving character. For example, the decimal values for ASCII characters 0-9 are 48-57 (www.AsciiTable.com 2010). Therefore the ASCII character ‘8’ has a decimal value of 56. Subtracting the ASCII ‘0’ (which is 48) leaves the decimal value 8.

The speed set point has a leading ‘1’ and the manual set point a leading ‘2’. Characters are sent one at a time so code is required to decipher the characters and place them into the correct variables.

The code stores all analogue values in a temporary variable called ‘DigitValue’.

In pseudo code:

If there a digit, then

- Multiply last ‘DigitValue’ by 10, then add the new decimal value of the digit to the new DigitValue.
- Keep doing this with each new digit until a ‘/’ is detected.

After the ‘/’ is detected, determine if there is a leading 1 or a leading 2. Extract the value by removing the leading 1 or 2 and store the value into either the speed set-point or manual set-point respectively, ensuring that the variable ‘DigitValue’ is returned to 0 ready for the next analogue value.

5.8.2.2 Digital Signals from Phone

The digital values sent from the phone have been all chosen as alphabet characters. This decision was made to ensure that digits sent are for analogues and digital signals are for digitals. An upper case character will make a Boolean variable ‘true’, while the lower case character will make the same Boolean variable ‘false’.

Table 5-2: Arduino Digital Data

Type	Character	Function

Digital values being turned On and Off	B(on)
	b(off)
		Brake

	R(on)
	r(off)
		Ratchet Mode

	M(on)
	m(off)
		Manual Output

	C (on) c (off)	Speed Control Mode
Digital values as a one shot signal	A	Calibrate Accelerometer
	L	Tare Load Strain Gauge
	S	Reset Max Speed
	F	Reset Max Force

5.8.3 Sensors

5.8.3.1 Accelerometer

The accelerometer is an MMA7361 accelerometer that is powered by 5 volts and generates three analogue outputs representing each axis. Two sensitivities can be selected, 1.5 g and 6 g via software or a selectable switch. This application uses the 6g sensitivity and therefore has a sensitivity of 206 mV/g +- 15.5 mV (Freescale Semiconductor 2008).

The 3.3 V output from the voltage regulator on-board the Arduino supplies the accelerometer. The analogue reference pin (AREF) is also supplied by the same 3.3 V supply.

An Arduino library was sourced online (jeroendoggen 2012) which allows for calibration, as well as retrieval of the axis accelerometer readings.

The total acceleration force is determined by the equation:

$$a_{total} = \sqrt{a_x{}^2 + a_y{}^2 + a_z{}^2} \quad \textbf{(5-27)}$$

Note that the total acceleration should always be 1 for a non-moving object due to the acceleration of gravity.

A first order lag digital filter is used to remove any unwanted noise from the accelerometer. To determine the filter settings, the maximum response time, sampling period and amount of change required were determined.

The scan rate of the code is determined to be 5 ms on average. Therefore the sampling period T_s is 5 ms. The maximum response time is experimentally determined to be half of the time it takes for the arm to reach a distance of 200 mm at 3 m/s and is determined to be 66 ms.

$$T_{200} = \frac{Dis\tan ce}{Speed} = \frac{0.2m}{3m/s} = 66.\overline{6}ms \quad \textbf{(5-28)}$$

To allow an adequate response time, the response time was decided to be 1/3 of the time required and therefore:

$$T_r = \frac{T_{200}}{3} = 22ms$$

With a desired final value of 90 % real value within 66 ms, the following formula was used to determine the filter coefficient k. With Fr = 0.9. The filter factor is determined by.

With a first order filter, the time to reach 63.2 % $\left(1-e^{-1}\right)$ is τ in the equation:

$$1-e^{-\frac{T_s}{\tau}} \qquad \textbf{(5-29)}$$

where T_s is the scan period. To allow the equation to account for times other than the time constant of 63.2 %, the natural logarithm of the final ratio is equated by the following equation:

$$\ln(1-Fr) \qquad \textbf{(5-30)}$$

Therefore to equate the filter constant (k) with inputs of the scan period T_s, the response time T_s and the % of final value to be reached within the response time is:

$$k = 1-e^{\ln(1-Fr)\times T_s/T_r} \qquad \textbf{(5-31)}$$

Therefore, the filter coefficient to reach 90 % within 22 ms with a scan time of 5 ms is;

$$k = 1-e^{\ln(1-0.9)\times 0.005/0.022} = 0.407$$

To implement, the following code was used (only x axis shown);

```
Ax = Ax * (1.00 - FilterAcc) + AxRaw * FilterAcc;
```

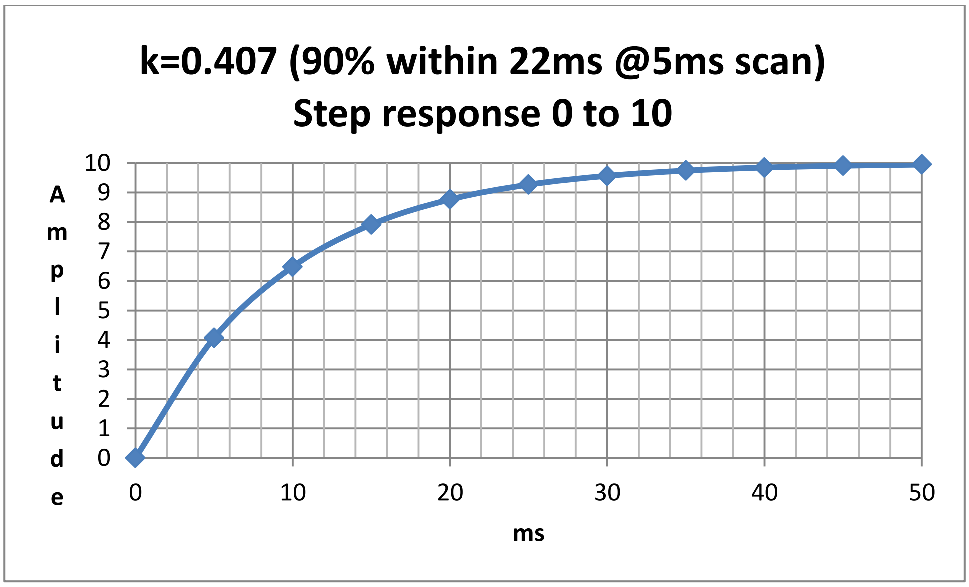


Figure 5-12: Filter response to step input

To calculate the overall force from 3 axis, the equation (5-27) was used;

$$a_{total} = \sqrt{a_x^{\ 2} + a_y^{\ 2} + a_z^{\ 2}}$$

```
TotalAccel = sqrt(sq(float(Ax))+ sq(float(Ay))+ sq(float(Az)));
```

These equations then form the code which is used in two other areas. The acceleration is used in the PID controller and also used to record the highest impact recording on the android application.

5.8.3.2 Speed Sensor

The speed sensor is used for the PID control and to display the highest speed measurement on the android application.

The elbow joint speed sensor used is a potentiometer connected to the centre of the shaft. The resistance equates to position and the change in resistance determines the speed. All angles are in degrees.

Angular Position (θ) is proportional to resistance (Ω).

```
Position = (float(Pot) * 360 / 1023) + Pos_Offset;
```

Angular Velocity **(ω) =** $\frac{d\theta}{dt}$ **.. (5-32)**

Fist Velocity = $\frac{\omega \cdot (2 \cdot \pi \cdot r)}{360}$ **..5-33)**

Where r is the radius from the joint to the centre of the fist (default = 300mm or 0.3m).

The resistance of the POT is 10 k**Ω**, which is converted as an analogue to 0-1023. To convert the analogue input to degrees, an Arduino mapping function is used.

The offset is determined when the potentiometer is first installed and should not require calibration. The offset is designed to allow the extended arm to be 0 degrees and measures a positive value when the arm is in flexion.

The below code segment only executes if the time between the last scan and this scan (dt) is greater than 5 ms. This is to prevent small numbers causing errors in the calculation. The change in time and position are both approximated by the difference between a previous value and the current value.

```
currentPotMilli = millis();

if (currentPotMilli - previousPotMilli > 5)

{
Speed = -(((Position - PositionOld) * 2.00 * PI * Radius / 360.00)
/ max(1, (currentPotMilli - previousPotMilli)));

PositionOld = Position;
previousPotMilli = currentPotMilli;

}
```

5.8.3.3 Strain Gauge

The strain gauge is setup via library functions. The functions are to set the scale and tare the sensor to zero. Note that the calibration factor will be determined during the initial build.

```
scale.set_scale(LC_Cal_Factor);//Adjust to calibration factor
scale.tare(); // Tare the load cell to zero
```

Following the initial setup, the strain gauge is to be calibrated by sending an ‘L’ character via serial communication.

```
else if (recd_dat == 'L') {  //*****CALIBRATE LOAD CELL
    scale.tare();
    recd_dat = 0;
```

The strain gauge value is returned with the calibration factor and offset from the tare applied with the following line of code.

```
StrainGauge = scale.get_units();
```

The strain gauge is used in the ratchet mode of operation, so further code design is within the ratchet mode section.

5.8.3.4 Position Sensor

The position sensor is a simple potentiometer. The potentiometer value is 10 kΩ and is a 1 resolution potentiometer. The 10 kΩ was chosen to ensure that the current into the Arduino was safe and also limits the power consumption.

I=5/10 kΩ = 0.5 mA

The datasheet application notes for the ATmega328 (Atmel 2009) states in section 23.6.1 that the ADC is optimised for analogue signals with an impedance of 10 k Ω or less for the sampling time to be negligible. If greater impedances are used, then the sampling time will depend on how long the source takes to charge a 14 pF capacitor in the ATmega circuit.

The following code maps the 0-1023 Arduino signal (representing 0-5V) and converts it to degrees by dividing the value by 1023 and multiplying by 360 degrees.

```
Pot = (analogRead(SpeedSens)); //Input A4 0-1023 = 360 degrees

Position = (float(Pot) * 360 / 1023) + Pos_Offset;

currentPotMilli = millis();
```

The following code then converts the position into speed by the taking the derivative of speed;

$$\omega = \frac{d\theta}{dt} \quad \text{(5-34)}$$

and;

$$dis\tan ce = \frac{(\theta_2 - \theta_1)2\pi \cdot r}{360} \quad \text{(5-35)}$$

Therefore;

$$Speed = \frac{d[(\theta_2 - \theta_1)2\pi \cdot r]}{360 \cdot dt} \quad \text{(5-36)}$$

```
  if (currentPotMilli - previousPotMilli > 5)
{
Speed = -( ((Position - PositionOld)/360 * 2.00 * PI * Radius) /
max(1, (currentPotMilli - previousPotMilli))); //mm/ms, or m/s
PositionOld = Position;
previousPotMilli = currentPotMilli;
}
```

5.8.4 Output data to brake

5.8.4.1 PID algorithm

The PID algorithm includes a proportional gain, integral action and derivative action. The control is a modified traditional PID control, in that the derivative action comes from an accelerometer, which is inherently the derivative of the speed for speed control.

The error is first calculated between the speed set-point from the Arduino (with a set-point range of 0-100 %) and the actual speed. The set-point range has been converted to 3 m/s to ensure that the maximum value of 3.3 m/s as determined in section 4.2. Therefore the equation is;

$$Error = (Speed \times 33.3) - SpeedSP \quad \textbf{(5-37)}$$

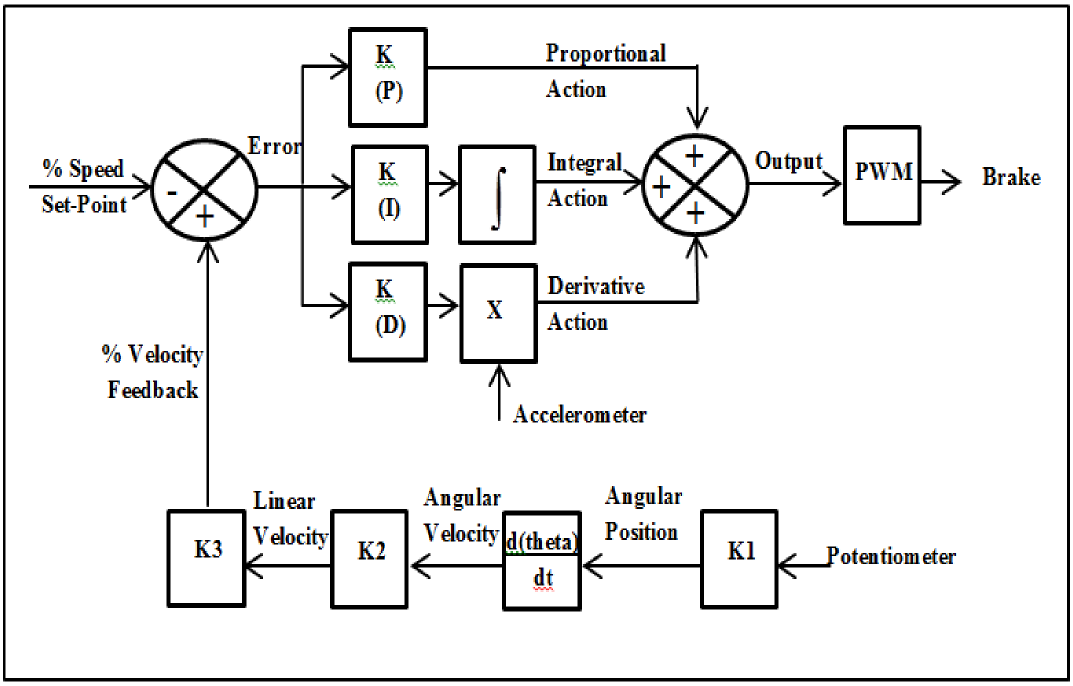


Figure 5-13: Speed PID Controller

```
if(Auto == true){
Error = max(0, (Speed*33.3) - SpeedSP); //50 is the conversion to
100% where 3 m/s = 100%
GainOut = Error*P_Val;
if (Error > 0){
  IntegralOut = IntegralOut + Error * I_Val;
  }
  else{IntegralOut=0;}
DerivativeOut = Error*max(0,(TotalAccel-100))*D_Val;
PIDOut = DerivativeOut+IntegralOut+GainOut;
BrakeCntrl = round(PIDOut*2.55);
analogWrite(BrakePwm, BrakeCntrl); //Writes the analogue to the
output pin (11).
}
```

5.8.4.2 Brake on

Analogue brake control is achieved by using the Pulse Width Modulation (PWM) output functionality of the Arduino. The analogue output ranges from 0 to 255. The default frequency is 490 Hz, which does not change during analogue output. What changes is the duty cycle, or the ratio of on and off, with 0 being at a constant 0 volts, 255 being at a constant 5 volts and 127 being at 5 volts for half the time and 0 volts for the other half. This output then drives the magnetic brake driver circuit.

5.8.4.3 Electronic Ratchet Braking

The electronic ratchet design not only allows the DSD to extend the arm into a straightened position. With the arm extended to the 90 degree mark no damage can be done to the face (almost fully extended).

In pseudo code, the idea is;

If Ratchet mode is on then:

- If the strain gauge is measuring force towards the face or the speed is moving towards the face and the position is less than 90 degrees then fully apply the brake.
- If the force is away from the face, then release the brake.

If the ratchet mode is not on then just brake!

```
void Braking() {
    if (Ratchet == true) {  //If the ratchet is on, then allow
only forward movement until 90 degrees is reached (which is seen
as a safe distance)
      if ((StrainGauge > 0.15 || Speed > 1) && Position < 90) {
//!!!!!!!!!!!!!!determine from demo trials
       // Serial.println("RATCHET on");For debugging
        analogWrite(BrakePwm, 255);
      }
      if (StrainGauge < -0.15) {
        analogWrite(BrakePwm, 0);
      }
    }
    else {
      analogWrite(BrakePwm, 255);
    //  Serial.println("No Rat Brake");
      //digitalWrite(BrakeCntrl, HIGH);
    }
```

5.8.5 Data transfer to phone

The phone accepts data ‘printed’ onto the Bluetooth serial signal from the Arduino. This is used by the ‘Serial.print’ command. Three items are to be displayed on the phone, being maximum speed, maximum force and the output from the strain gauge.

To let the phone know that there are 3 analogue values that need to be stored in different variables, an ‘An,’ is sent as leading characters. The phone then detects this and separates the analogues by a comma. Therefore the print command is;

```
Serial.print("An,");Serial.print(MaxSpeed,1);Serial.print(",");
Serial.print(MaxForce,2);Serial.print(",");Serial.println(StrainGa
uge);
```

5.9 Brake Output

There are many braking devices available on the market, however with the research completed, the simple electromagnetic brake was the device which had the advantage of being an off the shelf device, comparatively light, simple to drive and easy to integrate into a wearable device.

To drive the electromagnetic brake, a 24 VDC supply is switched via MOSFET transistor which is driven from the Arduino Pulse Width Modulated output.

A conventional transistor was considered, however low power usage is a requirement. The MOSFET is either fully off or fully on, so there is very little volt drop across the MOSFET when conducting and no current when not conducting and therefore has very little power loss when compared to driving a transistor under its saturation limit.

5.9.1 Driver circuit

The driver circuit receives a 490 Hz PWM input from the Arduino and outputs a PWM 24 VDC signal to the brake. The brake is rated at 15 W at 24 V and therefore will draw a maximum 0.625 A.

The Harris Semiconductor HUF75339P3 N-channel MOSFET (Harris Semiconductor 2015) has been used. This was chosen due to the 75 A and 55 V maximum rating. It has a maximum Drain to Gate Voltage (R_{GS}) of ±20 V, with a maximum power dissipation of 200 W. It also has a rise time of 100 ns and a fall time of 70 ns. At 490 Hz, these speeds are more than adequate and the faster the speed, the less power is consumed.

Figure 5-14 shows the electronic brake driver circuit. D1 is used as a freewheeling diode to supress any voltage spikes that occur when the voltage is removed from the brakes inductive load. An IN4004 diode has been used with a 1 volt forward voltage and is rated to peak surge of 30 A at 400 VDC (Diodes Incorporated 2015). As soon as a spike reaches greater than 1 V it will be supressed.

D2 is a 1N4742A Zener diode which has been sized to protect the MOSFET gate from higher voltages than designed. The maximum rating is ±20 V, with the expected voltage from the Arduino being 5 V. The Zener will conduct at 9.1 V.

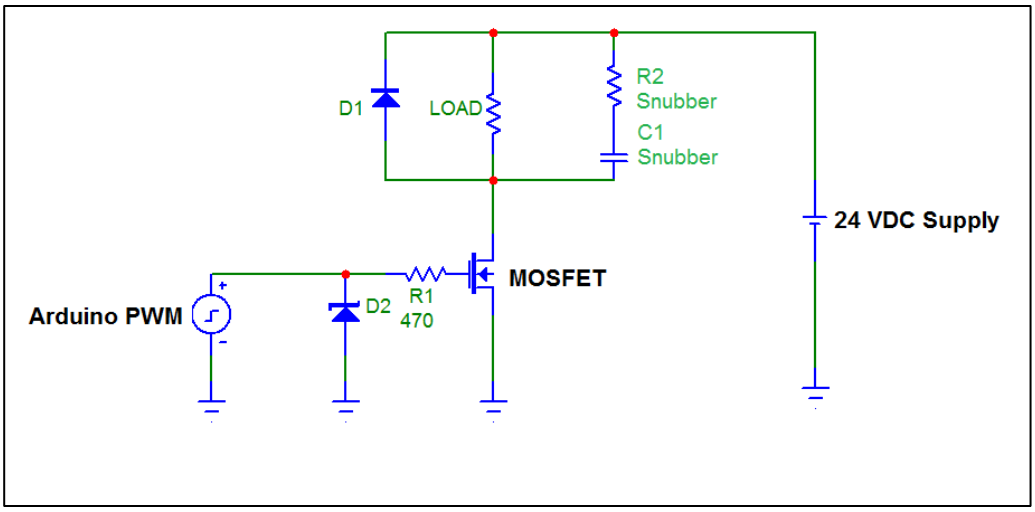


Figure 5-14: Brake Control Driver Circuit

R1 is designed for two purposes. Firstly to reduce the current that can be sourced from the Arduino to the maximum allowed by the Arduino of 40 mA (Atmel 2009). This is calculated by:

$$R_{\min} = \frac{V}{I} = \frac{5V}{40mA} = 125\Omega$$

Another reason for the resister is to eliminate any ringing in the MOSFET due to the gate capacitance.

A 150 Ω resister is used which reduces the current that can be sourced by the Arduino to 33.3 mA.

C1 is there to reduce any ringing that may be induced from the square wave PWM. This ringing is caused by parasitic inductances and capacitance in the circuitry. As the parasitic inductances and capacitances are unknown, C1 will be determined during the testing of the DSD.

5.9.2 Batteries

The batteries for the DSD will be Nickel-Metal Hydride (NiMH). These batteries were partly chosen to achieve a target 24 VDC, as three ‘9 V’ batteries can be used in series to give a total of 25.2 V (each battery has a true voltage of 8.4 VDC (7 cells at 1.2 V per cell)). NiMH have a high energy density compared to Nickel Cadmium (NiCad) batteries and have no charging problems like Lithium Ion batteries. They are also more environmentally friendly than NiCad and lead acid batteries (Ying et al. 2006).

The 9 V NiMH battery is commonly sold with a capacity of around 200 mA·h (Ebay.com.au 2015). Since the majority of the load is from the electromagnetic brake, with the driving circuit being negligible, the battery should last at the full load current of 0.625 A;

$$t = \frac{200mA \cdot h}{625mA} \times \frac{60\min}{1h} = 19.2\min$$

Under full braking, the brake will last 19.2 minutes, however due to the analogue style control and the electronic ratchet, the brake is expected to last much longer. The length of time the battery will last will be subject to rigorous testing in the future.

5.10 Design of Splint

The splint supports will be designed using 3D Solid Computer Aided Design (CAD) Modeller and subsequently printed with a 3D printer. The decision for printing the splint with a 3D printer was for a number of reasons;

- Integral to the design of the DSD is ease of reproduction by anyone with a 3D printer and access to simple tools. All parts are designed to be either off the shelf, or 3D printed, which brings the cost down and allows easy customisation.
- 3D printing allows rapid prototyping: This has allowed a ‘print and try’ design style to ensure throughout the design phase any issues are solved early.
- Easy reproduction: If a part breaks, or another part is required, then little time is wasted in reproducing another part.
- Customisable: If parts break, or need adjustments for different people, then the 3D models can be adjusted easily and further parts printed.

Note that for this dissertation, the 3D printed splint is designed to hold the components together so that testing can be completed and to prove the concept of

3D printing the parts. Testing has not been completed on the breaking points of the pieces and further improvement to the ergonomics of the DSD is required.

The CAD modelling program used will be OpenSCAD which is an open source free program that is written in a script file that renders the 3D model from the script. The scripting style makes customising objects easy, as shapes can be programmed as parameters in source code.

The complete set of parts drawings will be displayed in appendix B while the OpenSCAD source code for each of these parts is shown in Appendix C.

5.10.1 Initial design of Parts

This section describes the design of the first 3D print for the DSD. As discussed in previous sections, rapid prototyping is an advantage of 3D printers, so this initial design does not incorporate the intrinsic mounting of instrumentation, as the function of the main design is to be proven first.

The function of the 3D print is to house the electromagnetic brake, to allow free movement of the joint when the brake is not powered and allow the DSD to be strapped to the arm.

Below is picture of the brake. The rotating part is on the left, the fixed part on the right and the braking faces are shown;

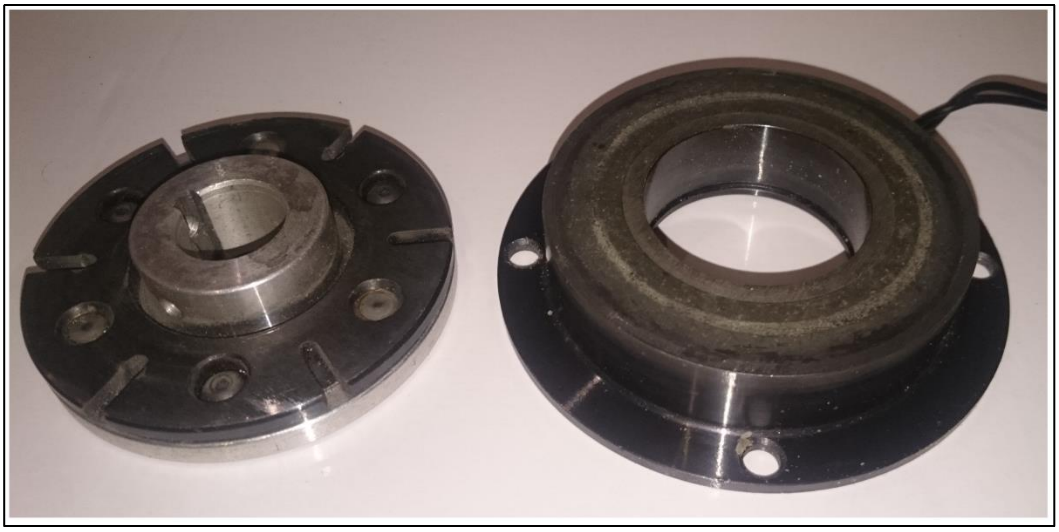


Figure 5-15: Electromagnetic Brake Pictured Apart

The next photo is the brake together, showing the position that they need to be held in for the splint;

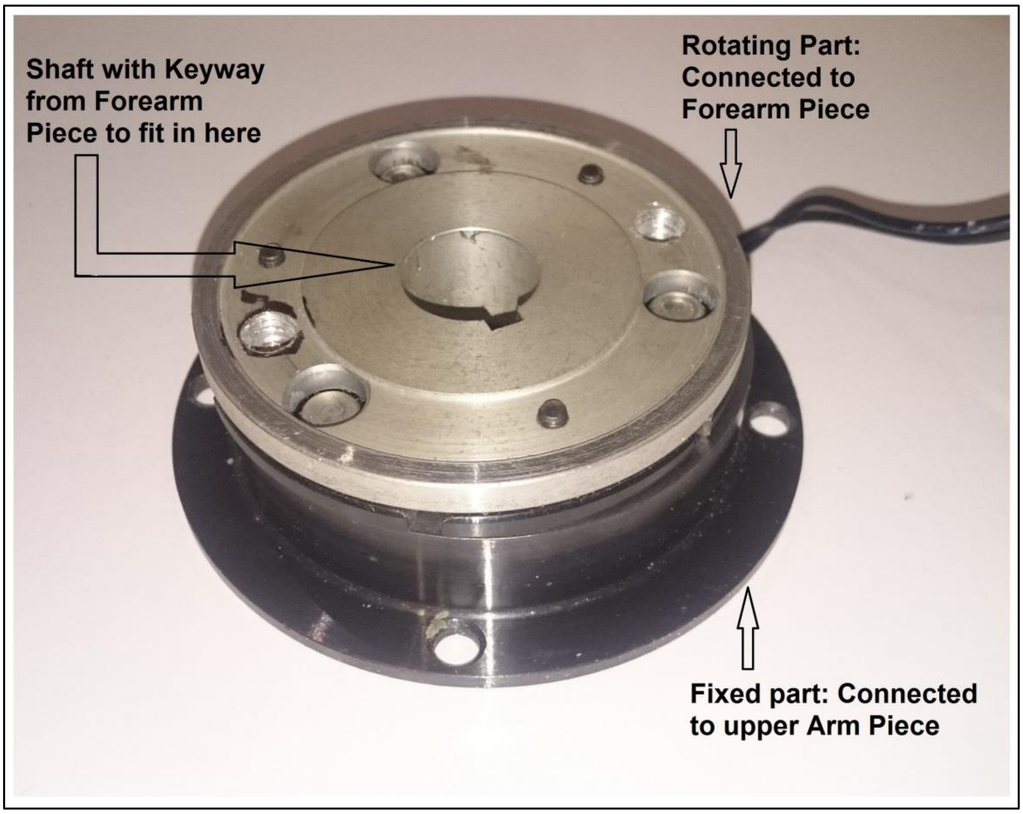


Figure 5-16: Electromagnetic Brake Parts Pictured Together

There are 3 main parts to the splint design, the bearing, the upper arm piece and the lower arm piece.

The bearing is based on a planetary gear set. It has herringbone splines on the gears, which stops the gears falling out and can handle axial loads. The bearing design was sourced from Thingiverse.com which is a website for the 3D printing community to share designs. Emmett Lalish is the author of this part and has given permission for others to modify his designs (Lalish 2013). Below is a picture of Emmett Lalish’s original design.

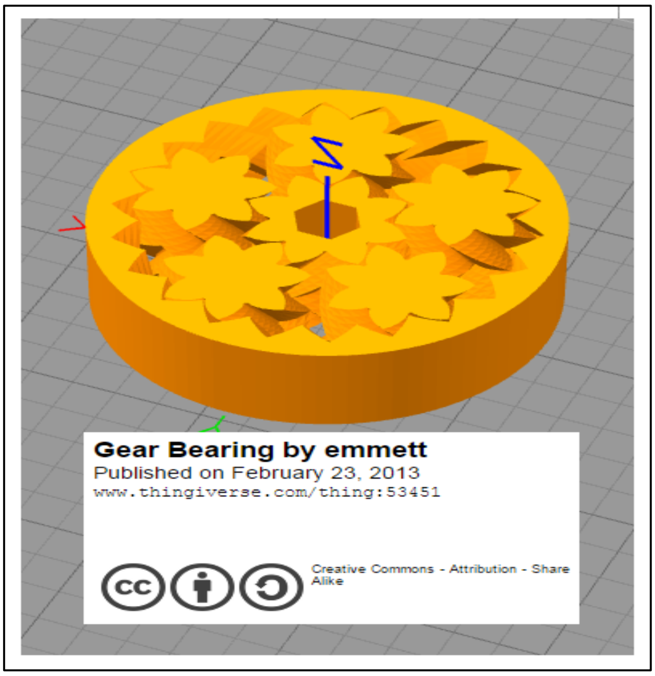

Gear Bearing by emmett
Published on February 23, 2013
www.thingiverse.com/thing:53451
Creative Commons - Attribution - Share Alike

Figure 5-17: Gear Bearing by Emmett. Source: www.thingiverse.com/thing:53451

The bearing was modified to incorporate a base plate which can be bolted onto the fixed part on the bottom of the brake. The keyed shaft is designed to fit into the rotating part which connects to the forearm.

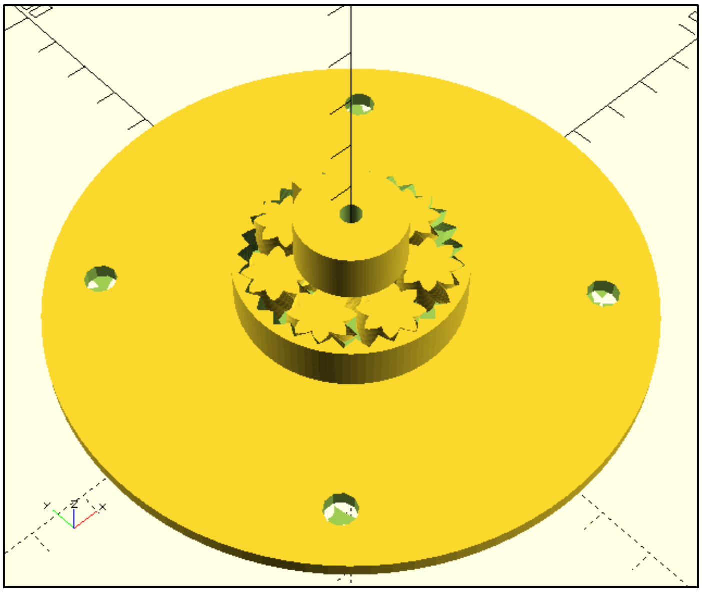


Figure 5-18: Bearing modifications

The upper arm piece bolts onto the top of the fixed part of the brake and has some slots to allow the splint to be secured to the upper arm.

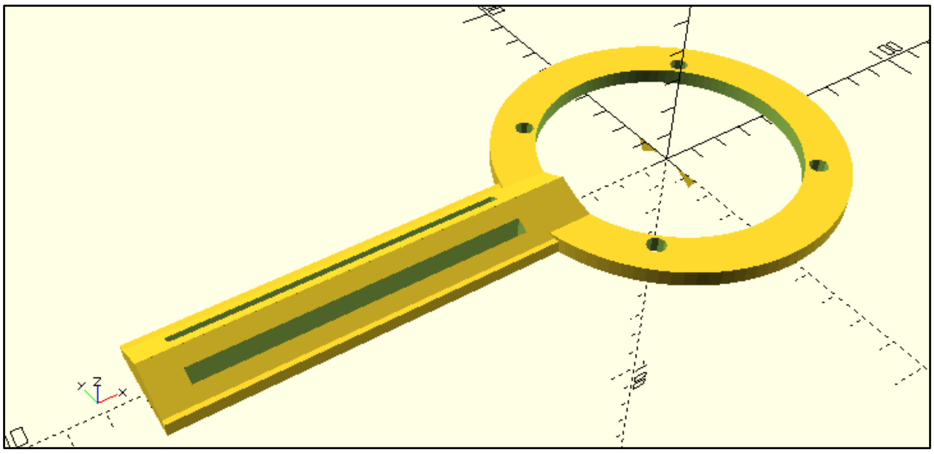


Figure 5-19: 3D Model, Upper Arm

The forearm piece has been designed to attach to the centre of the rotating part of the brake via the keyway and shaft. As with the upper-arm piece, slots exist to allow it to be strapped to the arm.

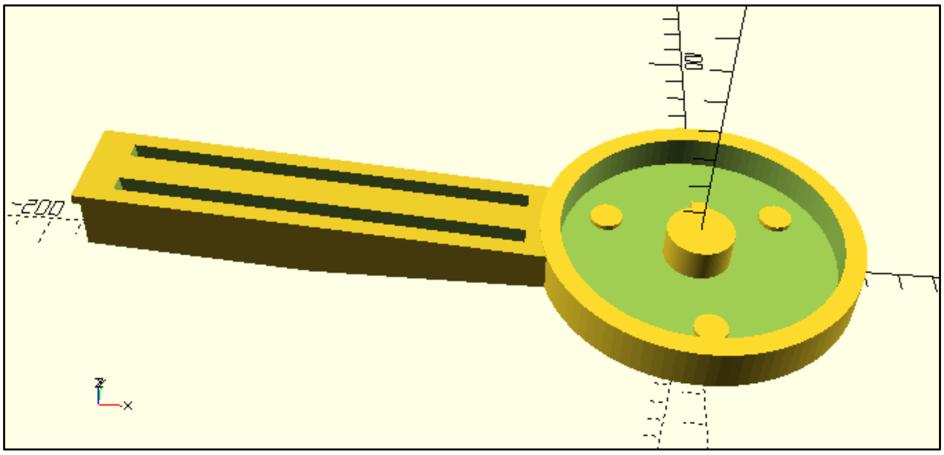


Figure 5-20: 3D Model, Forearm

The pieces fit together as per the diagram below. The bottom two parts sandwich the flange of the fixed part of the brake and bolt together, while the top part for the forearm will be screwed through the centre to hold it together.

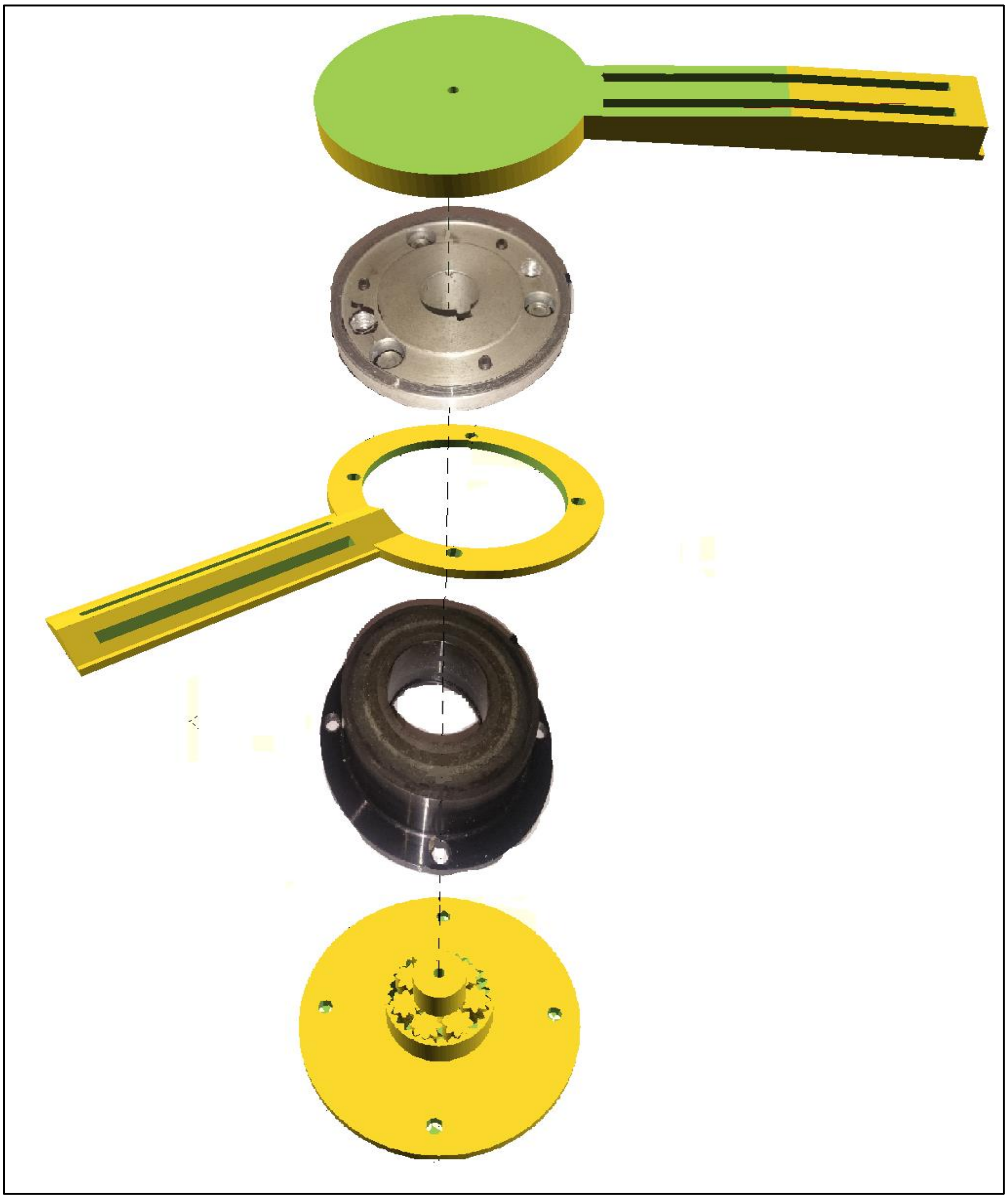


Figure 5-21: Exploded View of initial 3D Parts Design

The design of the 3d printed parts is continued in the build chapter.

Chapter 6. – Build and Testing

The build of the DSD had six stages, with the design altering slightly along the way:

1. Testing of the electronic brake to ensure that the brake performed as per the datasheet
2. Arduino coding
3. Build and testing of the brake driving circuit
4. Development of the Phone application to communicate with the DSD
5. 3D Printing of the splint material and modification to fit all the components into the DSD
6. Combining each element together to test the unit as a whole

6.1 Electromagnetic Brake Testing

The brake was tested to ensure that the braking torque was as per the datasheet. A temperature rise test was also completed to ensure that the brake did not get dangerously hot.

6.1.1 Brake torque test

To be able to test the brake for torque, the 3D modelled design was printed. The slots in the forearm piece intended for the straps were used to move a known weight along the length to determine the N·m torque that the brake would hold. The results were plotted.

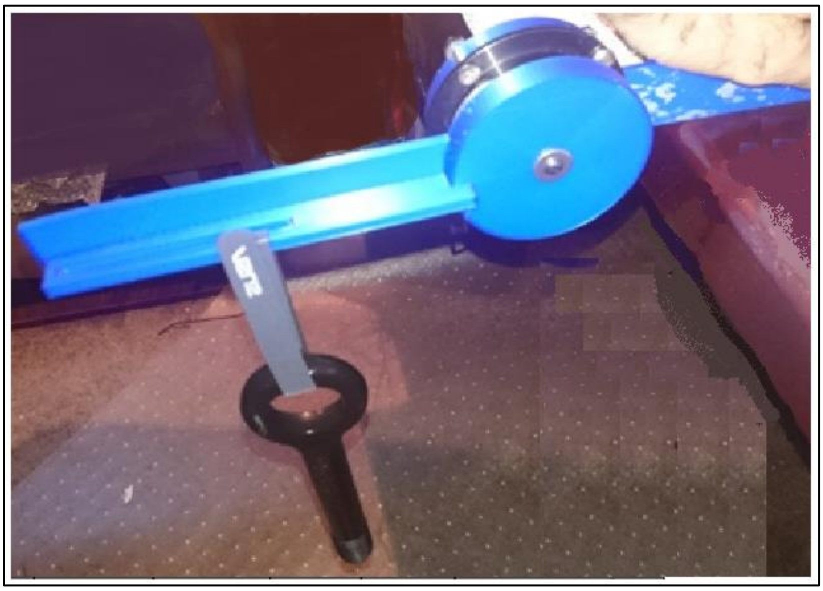


Figure 6-1: Testing the Electromagnetic Torque

The upper arm piece of the brake was held still while the forearm piece was positioned horizontal to the ground. A known weight was then suspended from the brake and the weight moved along until the brake started slipping. This was completed in 30 mA increments of current while recording the voltage and torque required to move the brake, and the weight and distance that would cause the brake to slip. The torque in N·m could then be determined and plotted. Below is a plot of the torque against voltage.

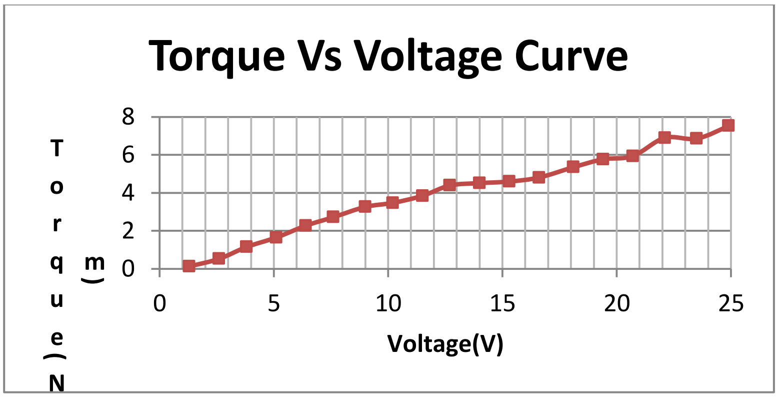


Figure 6-2: Chart of Brake Torque/Voltage

The above chart shows that the brake is fairly linear, however it does not reach the 10 N·m torque specified on the datasheet, however will still be satisfactory for the DSD.

The temperature of the brake was measured with an infrared temperature sensor. The temperature was taken every two minutes for 20 minutes, which is when the batteries will be depleted.

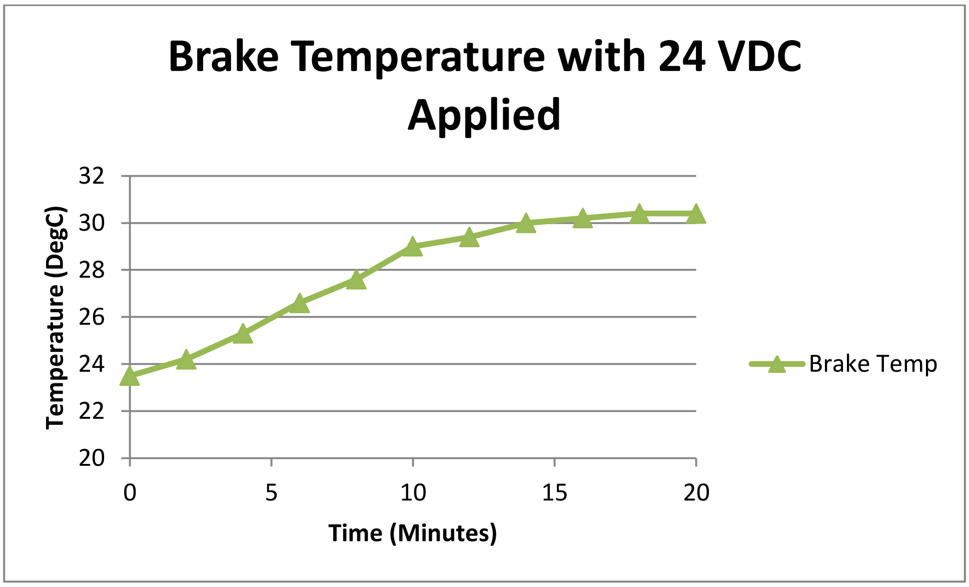


Figure 6-3: Brake Temperature with 24 V Applied

The temperature did rise, however the temperature reached an acceptable temperature of just over 30 degrees. The 3D printed plastic used is polylactic Acid (PLA) which has a glass transition temperature of between 60-65 °C (RepRap 2015), so there are no concerns with the temperatures reached by the brake.

6.2 Arduino Coding and circuit development

The code was written and downloaded to the Arduino. Initially the Arduino was wired up to a bread board to enable initial testing and debugging. Once the debugging was completed, a veroboard was used, which is an insulated board with copper strips on the back. The copper strips were cut to enable the below circuit to be wired:

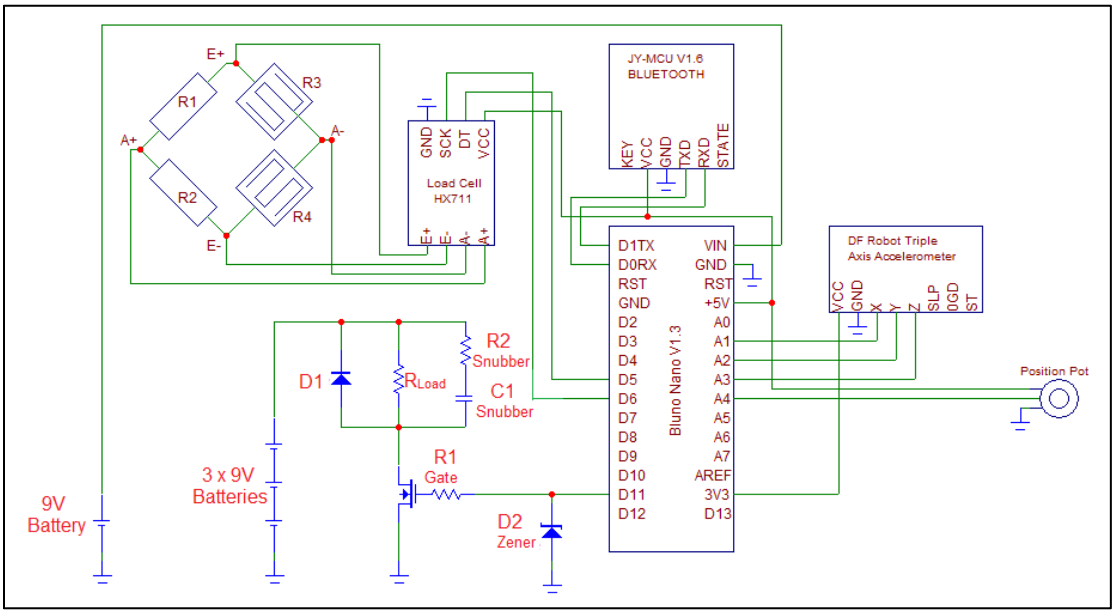
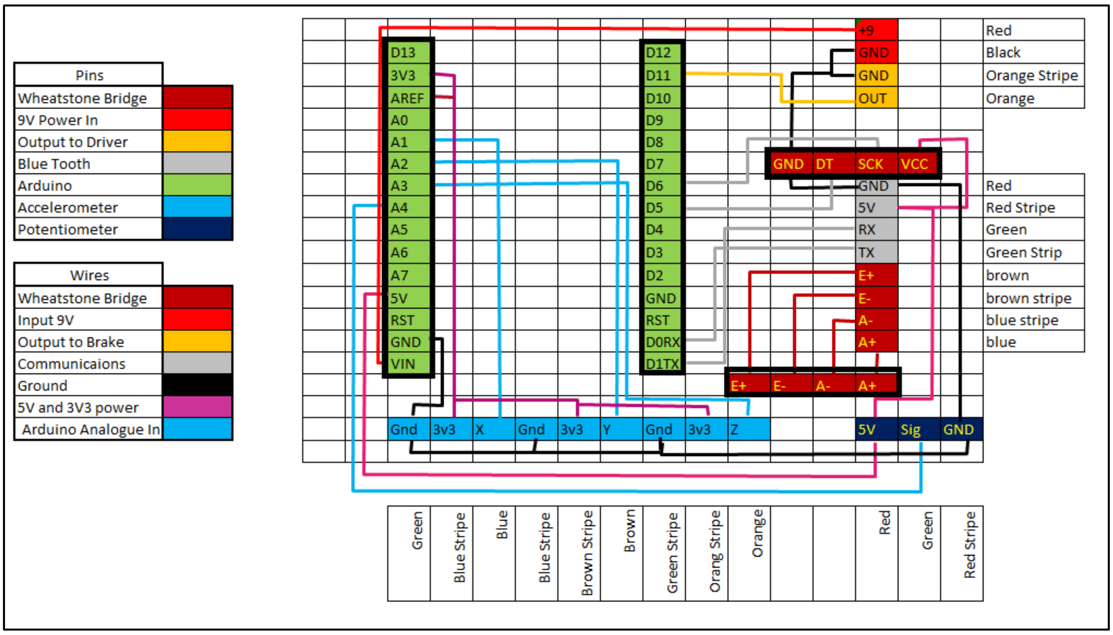


Figure 6-4: Arduino Circuit Diagram

Below is a diagram showing how the veroboard was wired. Chip sockets were used for the Arduino and Hx711 boards to allow removal of chips and replacement if required. The chip sockets are shown in the below figure with a bold black border. The other coloured squares in the grid are male connectors, which allow the external components to be plugged into the board. The colours indicated below and right of the main grid are wire colours used which are externally plugged to the board from the inputs and outputs. Internal wiring is shown as lines.



Pins	
Wheatstone Bridge	🟥
9V Power In	🟥
Output to Driver	🟧
Blue Tooth	⬜
Arduino	🟩
Accelerometer	🟦
Potentiometer	🟦

Wires	
Wheatstone Bridge	🟥
Input 9V	🟥
Output to Brake	🟧
Communicaions	⬜
Ground	⬛
5V and 3V3 power	🟪
Arduino Analogue In	🟦

Figure 6-5: Electronic Wiring Information

Below is a photo of the board wired up without the chips or plugs inserted, followed by a photo of the board with all plugs and chips connected.

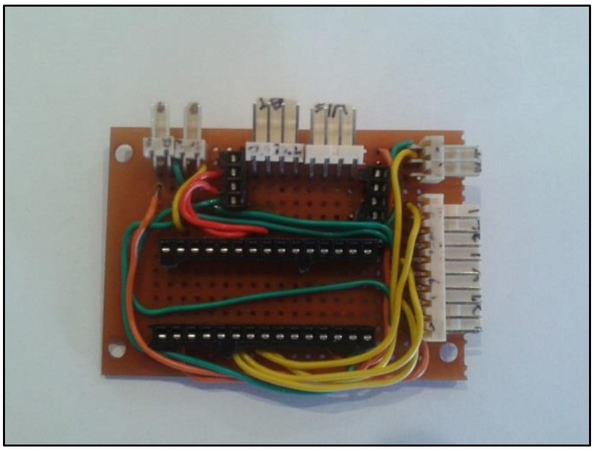


Figure 6-6: Veroboard without external equipment

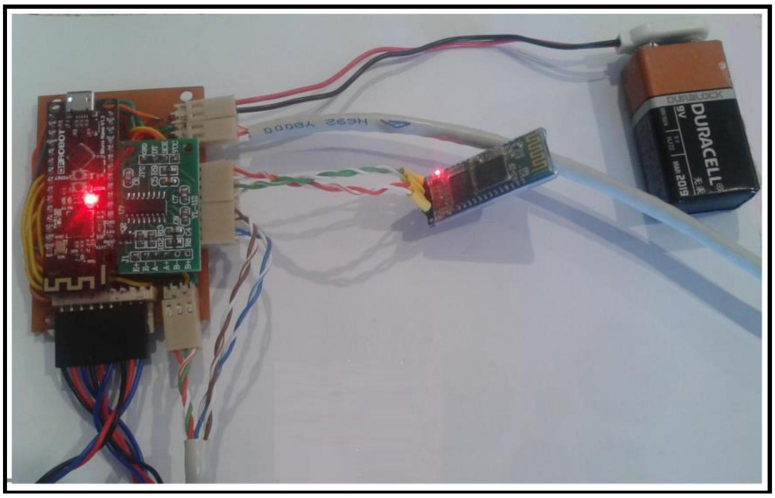


Figure 6-7: Veroboard with Components Connected

Once the circuits were connected, a 9 V Battery was used to power the device. Once powered, testing was completed to ensure that the sensors were connected correctly. A USB cable was connected to the Arduino to be able to modify the program if required and to allow the serial connection to display on the IDE's serial monitor.

The code was downloaded to the Arduino and the IDE serial monitor connected. Inserted into the code is commented out 'Serial Print' commands to print to the serial monitor screen parts of the code to test.

6.2.1 Testing inputs

The inputs were tested first. The raw input was printed to the serial monitor along with the calculated engineering values.

6.2.1.1 Potentiometer

The potentiometer value was tested, confirming that the position is converted to an accurate angle. This was tested as correct. Note that once placed into the DSD, the ‘Pos_Offset’ parameter will need to be adjusted to ensure that the open arm position is set at 0 ^{o}.

The speed value was tested to confirm that the speed value represented the change in position correctly.

The following table shows the calculated position, with a millisecond value and the speed value calculated. The calculated speed is confirmed to be correct with an insignificant difference due to the filter used.

Table 6-1: Confirmation of Speed Readings

Arduino Milliseconds	Calculated Δ time (ms)	Arduino Position (deg)	Calculated Δ Position (deg)	Arduino Speed (m/s)	Calculated Speed
1664		133.06		0	
1818	154	133.42	0.36	-0.01	-0.012
1972	154	133.42	0	0	0.000
2126	154	133.06	-0.36	0.01	0.012
2281	155	127.43	-5.63	0.19	0.190
2434	153	81.69	-45.74	1.55	1.565
2587	153	49.66	-32.03	1.09	1.096
2740	153	48.26	-1.4	0.05	0.048
2893	153	65.85	17.59	-0.6	-0.602
3048	155	84.15	18.3	-0.62	-0.618
3203	155	101.74	17.59	-0.6	-0.594
3357	154	117.58	15.84	-0.53	-0.539
3513	156	124.27	6.69	-0.23	-0.225
3666	153	122.86	-1.41	0.05	0.048
3819	153	81.33	-41.53	1.41	1.421
3972	153	32.77	-48.56	1.67	1.662
4126	154	41.22	8.45	-0.29	-0.287
4280	154	66.55	25.33	-0.87	-0.861
4433	153	92.6	26.05	-0.89	-0.891
4589	156	112.3	19.7	-0.67	-0.661

6.2.1.2 Accelerometer

The accelerometer was tested, with the x, y and z axis. Once calibrated, the values of the accelerometer were observed while the z axis was facing upwards. The reading was 100 on the z axis and around 0 on the x and y axis. The accelerometer was then moved in each direction (x y and z) and the measurements corresponded to the direction of movements.

On the following page is a graph showing the position and speed, as well as the accelerometer readings. Note that the accelerometer reading is 100 for 1 g and the speed has been multiplied by 100 so that it is represented with the same scale.

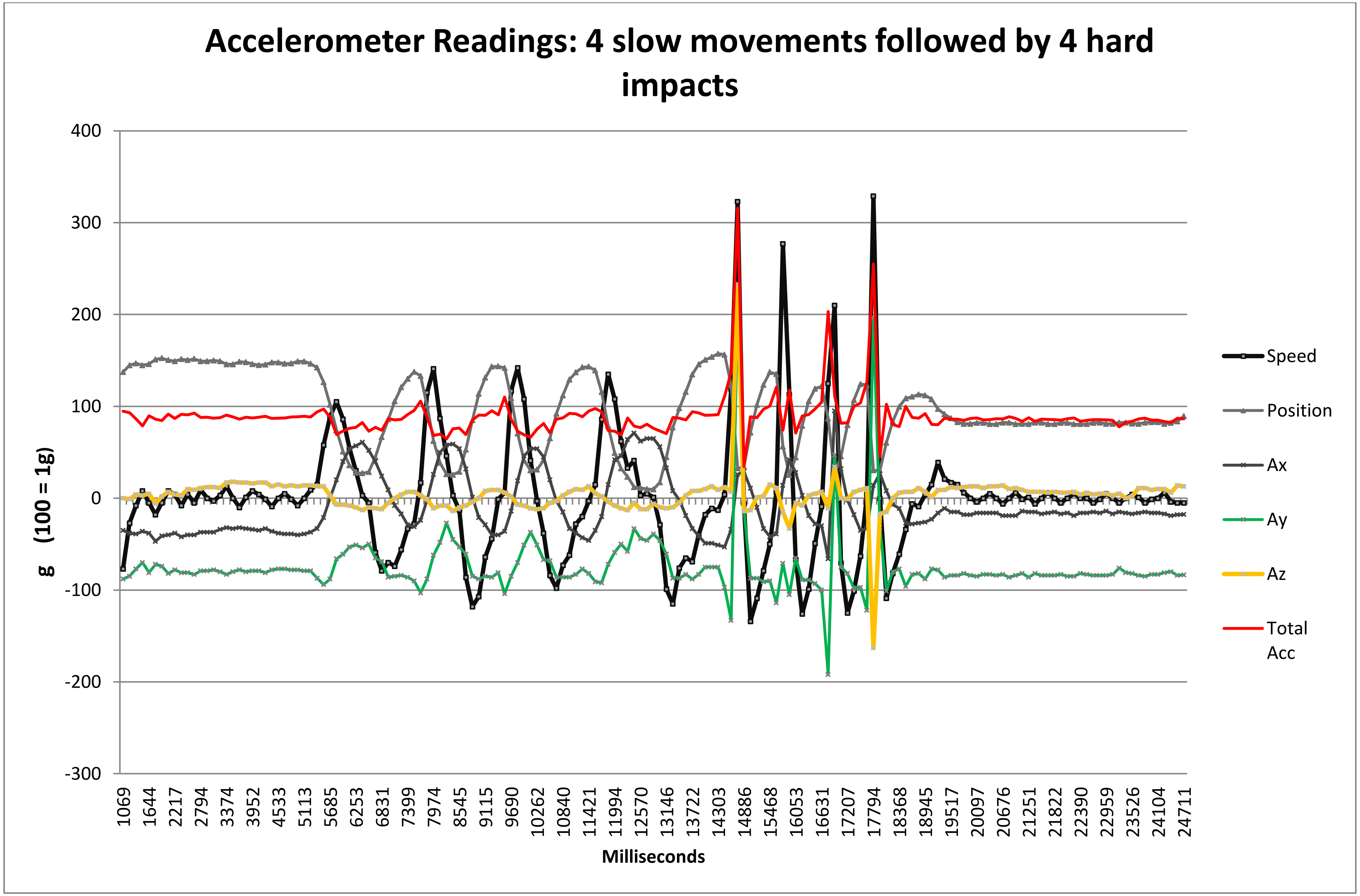


Figure 6-8: Accelerometer Graph

The above graph shows that the speed changes show corresponding accelerometer changes.

To ensure the accelerometer figure is correct, acceleration has been calculated from the change in speed and compared on the same graph with the accelerometer. Note that the accelerometer is total acceleration and therefore will always be positive. The equation for the calculated value is;

$$g_{CALC} = \frac{\left|\frac{dv}{dt}\right|}{9.8}$$

Where $\left|\frac{dv}{dt}\right|$ is estimated by new values and previous values of speed and time;

$$\left|\frac{dv}{dt}\right| = \left|\frac{v_{NEW} - v_{OLD}}{Time_{NEW} - Time_{OLD}}\right|$$

The accelerometer detects the acceleration of gravity, so the graph below has removed 1 g so that the calculated and accelerometer values can be compared. The raw data can be seen in Appendix E

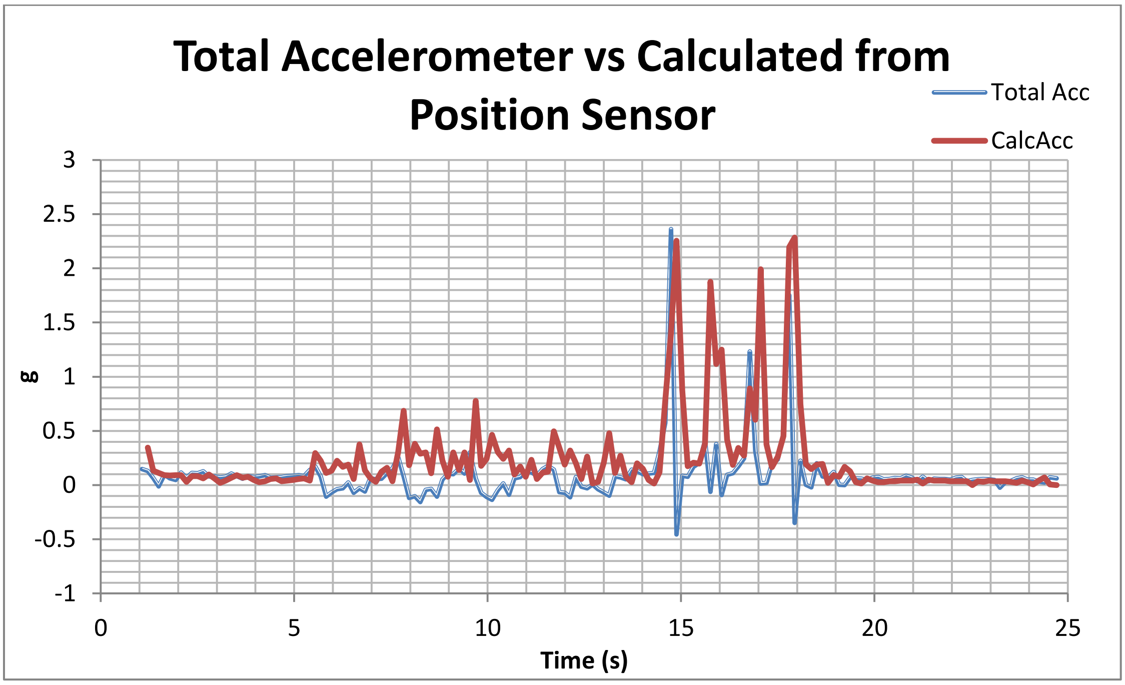


Figure 6-9: Accelerometer Vs Calculation from Position Sensor

The figure shows that there is a correlation between the two, however they are not exactly the same which is what was expected. The four slow movements were not detected as accurately as the calculated value form the position sensor. The decision was made to use the accelerometer, due to the advantage of measuring acceleration when the shoulder is being used for movement and also, the advantage of being able to measure impact more accurately.

6.3 Driver Circuit

Below is a picture of the brake circuit which has been soldered to a veroboard.

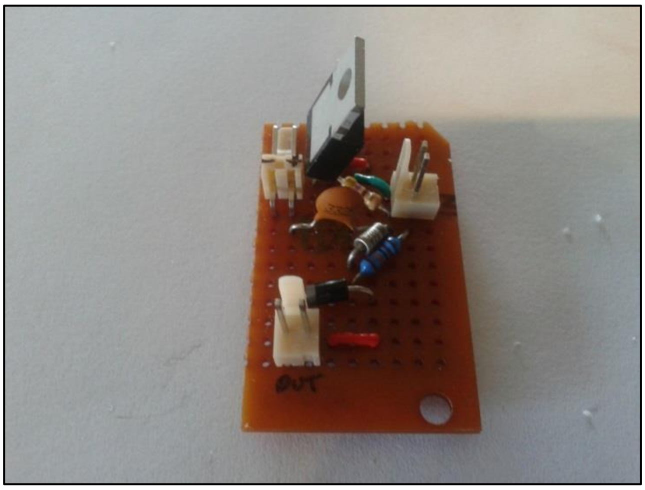


Figure 6-10: Driver Circuit Board

Once soldered, the brake unit was connected to the 3 batteries and inserted into a plastic box which was bought for the braking drive unit.

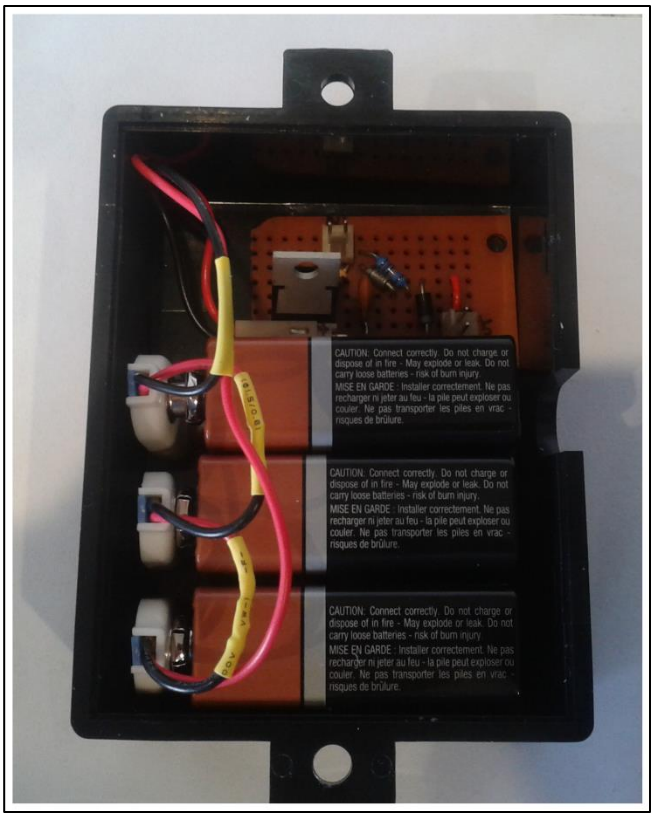
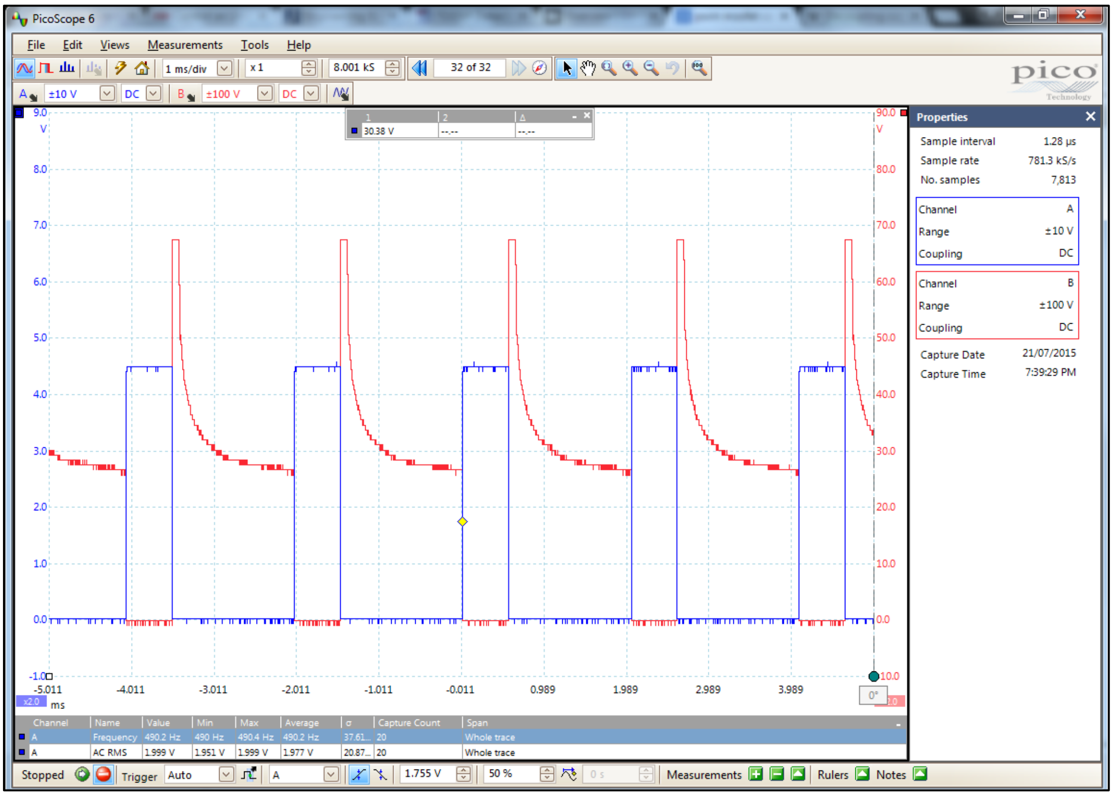

CAUTION: Connect correctly. Do not charge or dispose of in fire - May explode or leak. Do not carry loose batteries - risk of burn injury.
MISE EN GARDE : Installer correctement. Ne pas recharger ni jeter au feu - la pile peut exploser ou couler. Ne pas transporter les piles en vrac - risques de brûlure.
CAUTION: Connect correctly. Do not charge or dispose of in fire - May explode or leak. Do not carry loose batteries - risk of burn injury.
MISE EN GARDE : Installer correctement. Ne pas recharger ni jeter au feu - la pile peut exploser ou couler. Ne pas transporter les piles en vrac - risques de brûlure.
CAUTION: Connect correctly. Do not charge or dispose of in fire - May explode or leak. Do not carry loose batteries - risk of burn injury.
MISE EN GARDE : Installer correctement. Ne pas recharger ni jeter au feu - la pile peut exploser ou couler. Ne pas transporter les piles en vrac - risques de brûlure.

Figure 6-11: Driver Circuit with Batteries in Box

The brake drive unit was then connected to the Arduino and the brake. To test the brake drive circuitry and the manual control of the brake, the Arduino was put into manual mode via the IDE serial interface and the brake output was put to 25% (output of 64). Below is a figure of the initial scope trace



Properties

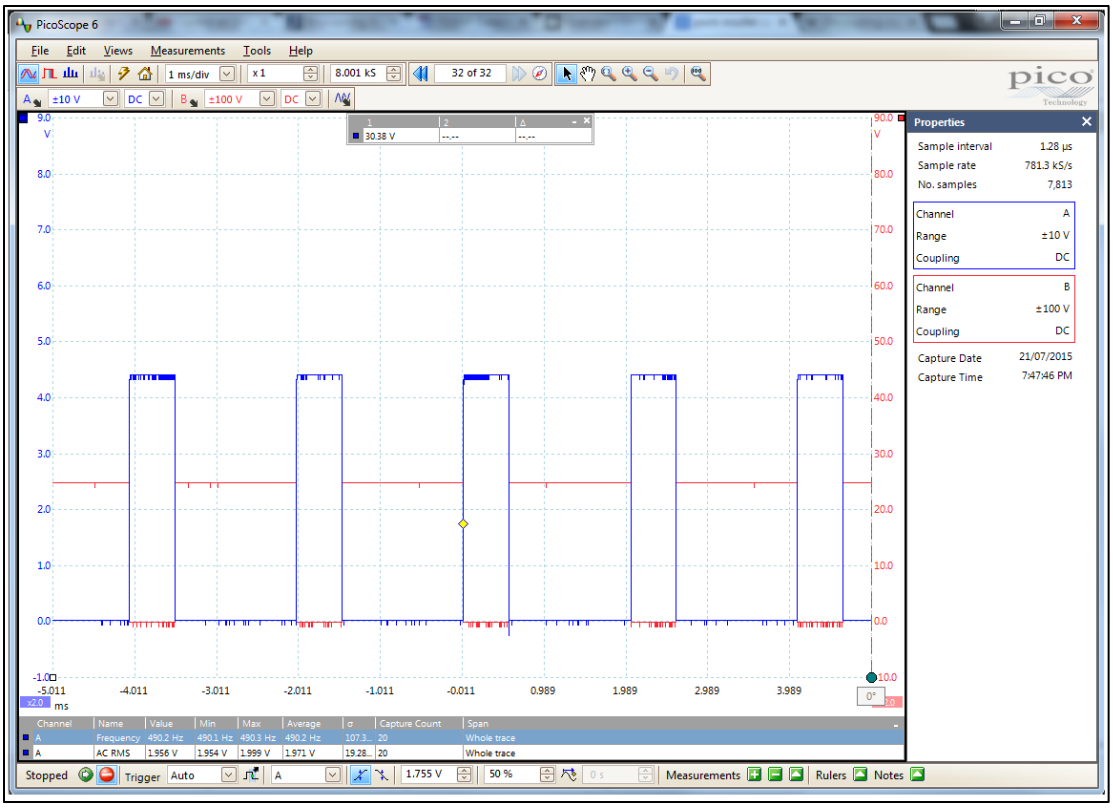
Sample interval	1.28 μs
Sample rate	781.3 kS/s
No. samples	7,813
Channel	A
Range	±10 V
Coupling	DC
Channel	B
Range	±100 V
Coupling	DC
Capture Date	21/07/2015
Capture Time	7:39:29 PM

Channel	Name	Value	Min	Max	Average	σ	Capture Count	Span
A	Frequency	490.2 Hz	490 Hz	490.4 Hz	490.2 Hz	37.61...	20	Whole trace
A	AC RMS	1.999 V	1.951 V	1.999 V	1.977 V	20.87...	20	Whole trace

Figure 6-12: PWM trace with faulty diode connection

The blue channel A is the PWM output from the Arduino, while the red channel B is output from the brake controller to the brake. The signal is inverted due to measurement being taken from the drain of the MOSFET so when the voltage is at 0 V it is conducting.

The red peaks have amplitude of around 67 V, which could not be sourced from the batteries, so exceeds the 55 V MOSFET rating. This is from back-EMF caused by the collapsing magnetic field from the brake which is as an inductor. D1 in the circuit is designed to stop this behaviour. On inspection, the diode was not connected properly. Once connected properly, the following trace was recorded on the scope:



Channel	Name	Value	Min	Max	Average	σ	Capture Count	Span
A	Frequency	490.2 Hz	490.1 Hz	490.3 Hz	490.2 Hz	107.3...	20	Whole trace
A	AC RMS	1.956 V	1.954 V	1.999 V	1.971 V	19.28...	20	Whole trace

Properties

Sample interval	1.28 µs
Sample rate	781.3 kS/s
No. samples	7,813
Channel	A
Range	±10 V
Coupling	DC
Channel	B
Range	±100 V
Coupling	DC
Capture Date	21/07/2015
Capture Time	7:47:46 PM

Figure 6-13: 490 Hz 25 % Output Trace

It now displays a nice square-wave, however the brake behaved like a speaker, amplifying a sound. The default PWM frequency of 490 Hz was used, which is within the audible range.

Options to solve this issue included using a capacitor on the input to the MOSFET, however the MOSFET would be controlled in the active linear region and would waste power. Another option is to avoid the audible range by increasing the frequency of the brake to something above 20 kHz (Loisiana State University 2015). This solution was explored.

6.3.1.1 Increasing the Frequency of the Brake Driver

Within the Arduino, the analogue write value is compared against the value of an 8-bit counter. Timer/counter Control Registers (TCCRnA and TCCRnB) are the main control bits that control the PWM outputs. The clock set bits (CS) of these control registers determine the pre-scaler which control the frequency of the PWM.

The frequency of the PWM is calculated by the clock set bits of this prescaler, of which the channel used for the brake uses the Control Register TCCR2B and the CS bits are stored in the three least significant bits of this register. The calculation for frequency is;

$$f_{PWM} = \frac{f_{clk.}}{N \times 510} \quad \text{(6-1)}$$

N is the pre-scaler factor with the CS bits as shown in the below table

Table 6-2: Arduino PWM Pre-scaler Values

CS Bits	N (Pre-scaler)	Frequency
001	1	31372.55
010	8	3921.57
011	32	980.39
100	64	490.20
101	128	245.10
110	256	122.55
111	1024	30.64

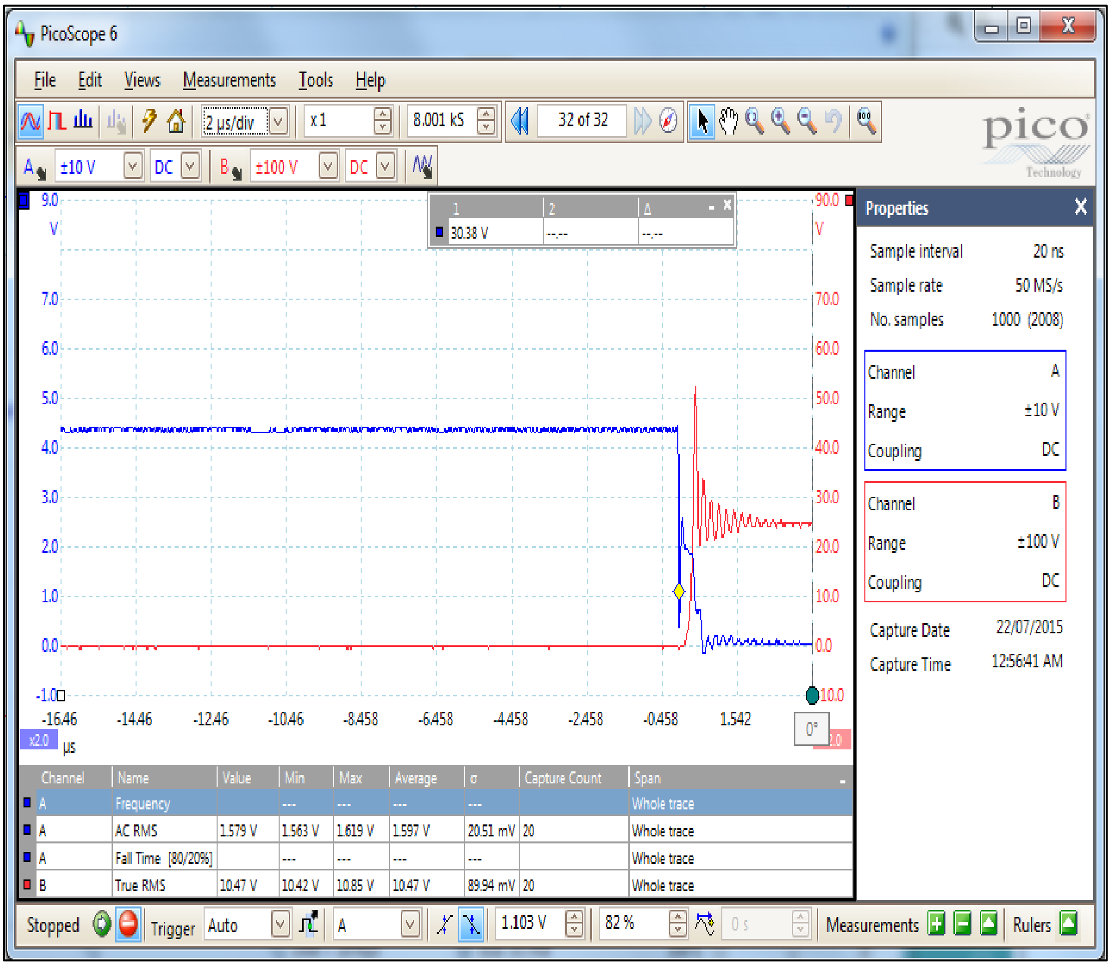
To achieve 31,372 Hz, the prescaler bits for TCCR2B is changed to 001.

This is achieved by the following code.

```
TCCR2B = TCCR2B & B11111000 | B00000001
```

The bitwise and (&) is to ensure that we keep the existing values of the register for the 5 most significant bits while the bitwise or (|) is used to enter the new CS bits.

Once this change was completed, the brake was tested again. The audible noise had completely disappeared, however when the scope was placed on the circuit, ringing was observed.



Channel	Name	Value	Min	Max	Average	σ	Capture Count	Span
A	Frequency		---	---	---	---		Whole trace
A	AC RMS	1.579 V	1.563 V	1.619 V	1.597 V	20.51 mV	20	Whole trace
A	Fall Time [80/20%]		---	---	---	---		Whole trace
B	True RMS	10.47 V	10.42 V	10.85 V	10.47 V	89.94 mV	20	Whole trace

Properties

Sample interval	20 ns
Sample rate	50 MS/s
No. samples	1000 (2008)
Channel	A
Range	±10 V
Coupling	DC
Channel	B
Range	±100 V
Coupling	DC
Capture Date	22/07/2015
Capture Time	12:56:41 AM

Stopped Trigger Auto A 1.103 V 82 % 0 s Measurements Rulers

Figure 6-14: PWM 32 kHz ringing

The ringing only occurred during a small period of time (about 2 µs), however the concern was that the voltage spiked up to over 50 V.

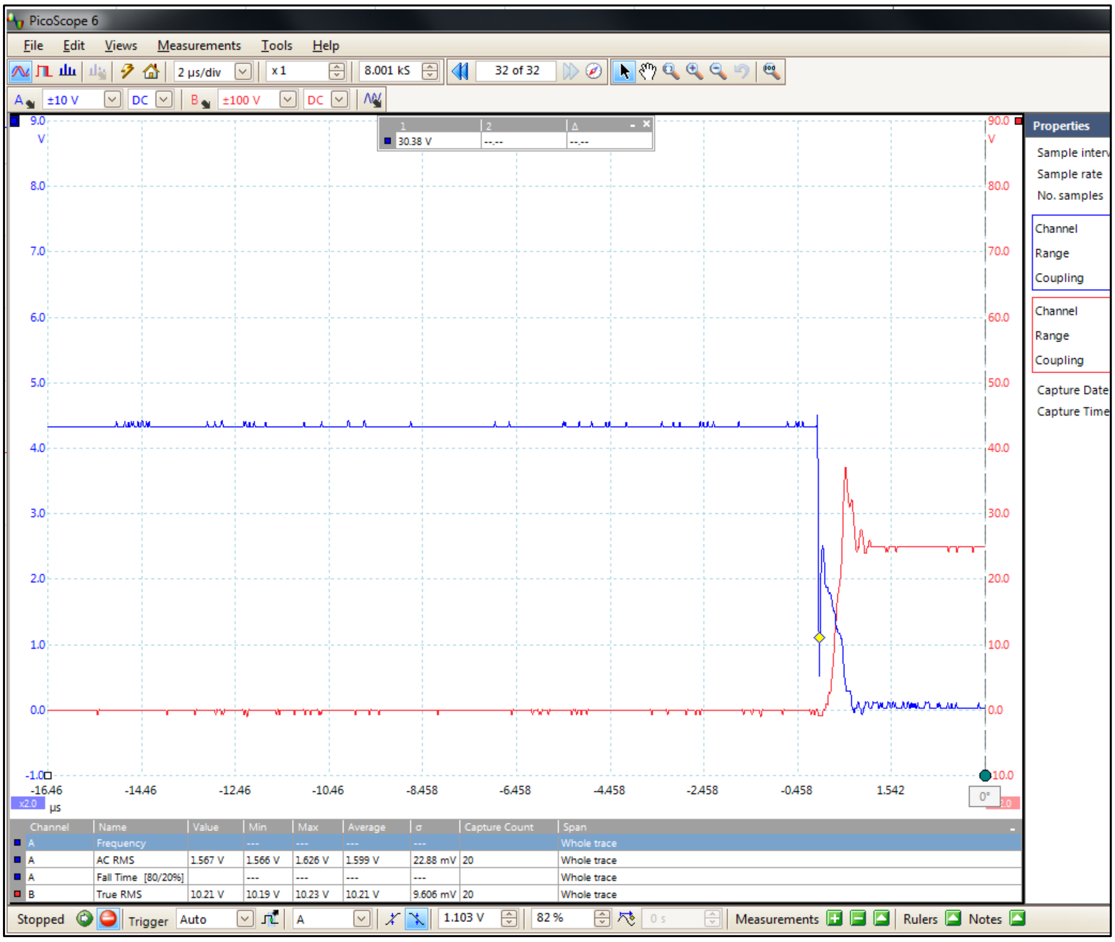
C1 is a placeholder capacitor to reduce any ringing that may be induced from the square wave PWM. This ringing was caused by parasitic inductances and capacitance in the circuitry. The addition of a capacitor dampened the response by becoming an RC snubber.

To reduce the ringing in the circuit at high frequencies, a number of techniques were used. These included;

- A capacitor across the load to smooth the output
- Increasing resistor size into the gate to reduce the gate ringing
- Shortening of the component leads to reduce circuit capacitance and inductances

Note that the output is not affected by the ringing. The objective of reducing the ringing is to minimise the voltage peaks that the circuitry has to deal with, ensuring long lasting componentry.

Trial and error was used for C1 and a value of 332 nF reduced the ringing. The reduction in peak voltage is from 51 V to 37 V, a reduction of 27.45 % and within allowable limits of the circuit.



2 µs/div, x 1, 8.001 kS, 32 of 32

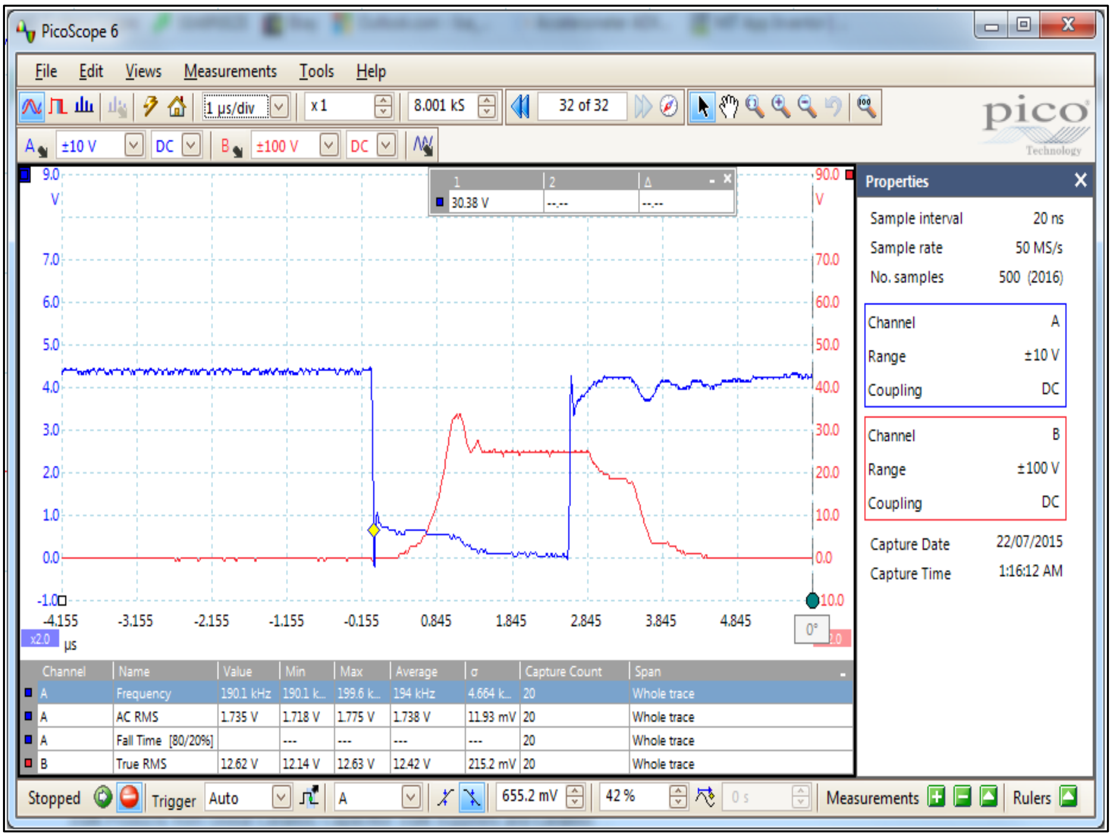
A ±10 V DC, B ±100 V DC

Channel	Name	Value	Min	Max	Average	σ	Capture Count	Span
A	Frequency		---	---	---	---		Whole trace
A	AC RMS	1.567 V	1.566 V	1.626 V	1.599 V	22.88 mV	20	Whole trace
A	Fall Time [80/20%]		---	---	---	---		Whole trace
B	True RMS	10.21 V	10.19 V	10.23 V	10.21 V	9.606 mV	20	Whole trace

Stopped, Trigger Auto, A, 1.103 V, 82 %, 0 s, Measurements, Rulers, Notes

Figure 6-15: Addition of 332 nF Capacitor

The resistance on the gate was also increased. With a resistance increased to 470 Ω the MOSFET drive circuit essentially swamped the drive circuit. A further reduction in ringing was obtained, however the response was slowed.



Channel	Name	Value	Min	Max	Average	σ	Capture Count	Span
A	Frequency	190.1 kHz	190.1 k...	199.6 k...	194 kHz	4.664 k...	20	Whole trace
A	AC RMS	1.735 V	1.718 V	1.775 V	1.738 V	11.93 mV	20	Whole trace
A	Fall Time [80/20%]		---	---	---	---	20	Whole trace
B	True RMS	12.62 V	12.14 V	12.63 V	12.42 V	215.2 mV	20	Whole trace

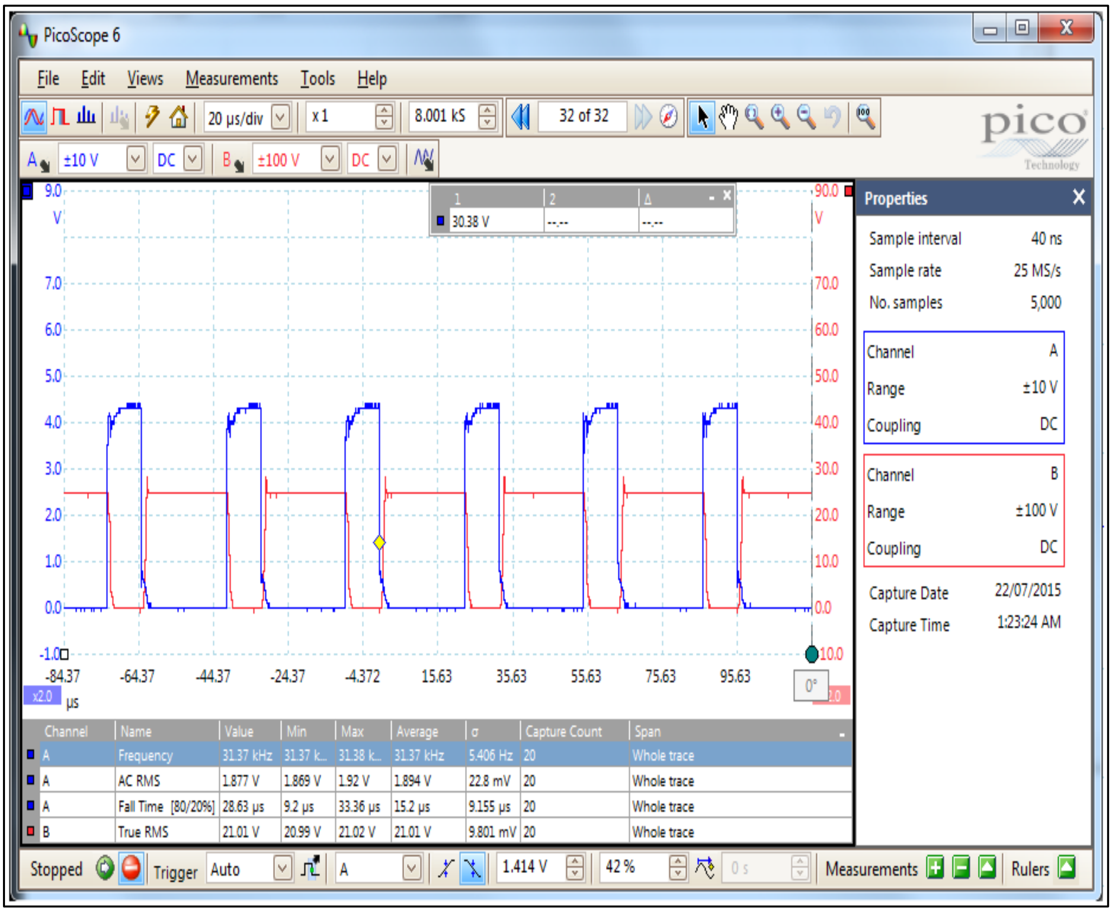
Properties

Sample interval	20 ns
Sample rate	50 MS/s
No. samples	500 (2016)
Channel	A
Range	±10 V
Coupling	DC
Channel	B
Range	±100 V
Coupling	DC
Capture Date	22/07/2015
Capture Time	1:16:12 AM

Figure 6-16: Addition of 470 Ohm Resistor in Gate circuit

The compromise from adding circuitry to smooth the ringing, is that a slower rise time means that the MOSFET will now spend less time in saturation. It will cause $I^{2\cdot}R$ losses and produce heat, however the temperature of the MOSFET was measured and there was no considerable temperature rise.

The PWM in perspective at 27 % duty cycle has the following image on the scope;



Properties

Sample interval	40 ns
Sample rate	25 MS/s
No. samples	5,000
Channel	A
Range	±10 V
Coupling	DC
Channel	B
Range	±100 V
Coupling	DC
Capture Date	22/07/2015
Capture Time	1:23:24 AM

Channel	Name	Value	Min	Max	Average	σ	Capture Count	Span
A	Frequency	31.37 kHz	31.37 k...	31.38 k...	31.37 kHz	5.406 Hz	20	Whole trace
A	AC RMS	1.877 V	1.869 V	1.92 V	1.894 V	22.8 mV	20	Whole trace
A	Fall Time [80/20%]	28.63 µs	9.2 µs	33.36 µs	15.2 µs	9.155 µs	20	Whole trace
B	True RMS	21.01 V	20.99 V	21.02 V	21.01 V	9.801 mV	20	Whole trace

Figure 6-17: PWM 32 kHz with Filtering

6.4 Phone Coding

The Massachusetts Institute of Technology's (MIT) App Inventor was utilised to develop the Android phone application. MIT administer the web based application originally developed by Google's Mark Friedman (MIT App Inventor 2015). App Inventor allows development of Android applications without text based coding. The coding is a visual based, drag-and-drop method where building blocks are used to develop the code.

The visual side of the application was developed within the 'Designer' tab, while the code side of the application was developed with the 'Blocks' tab.

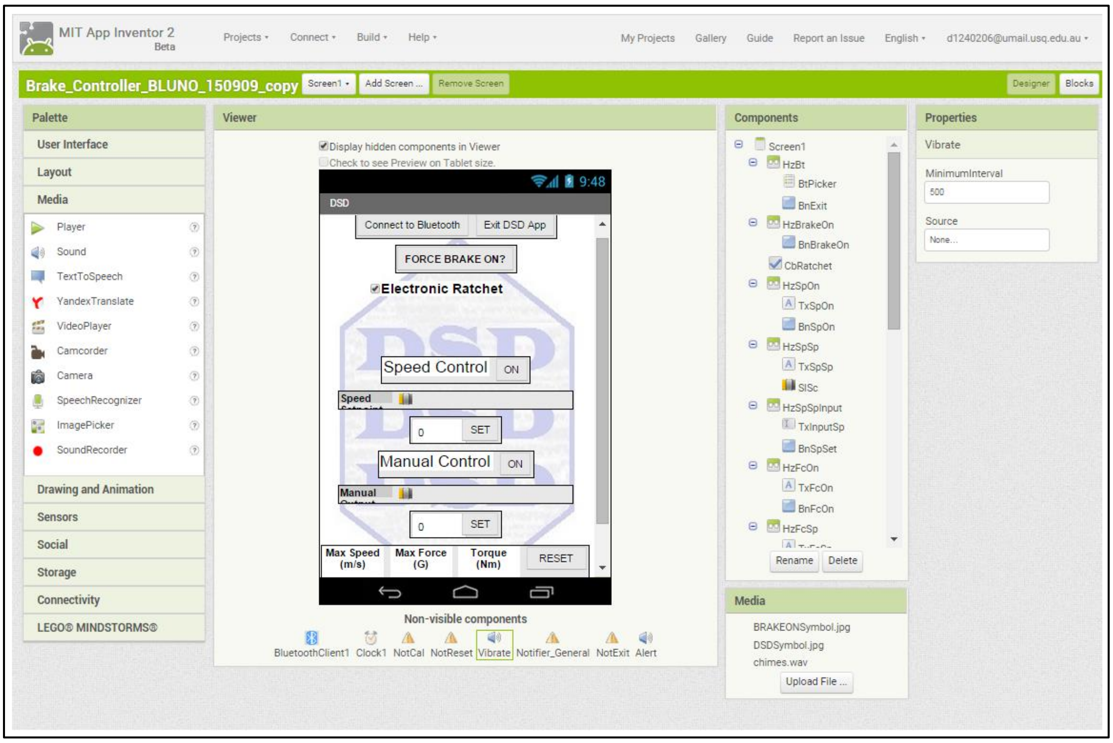
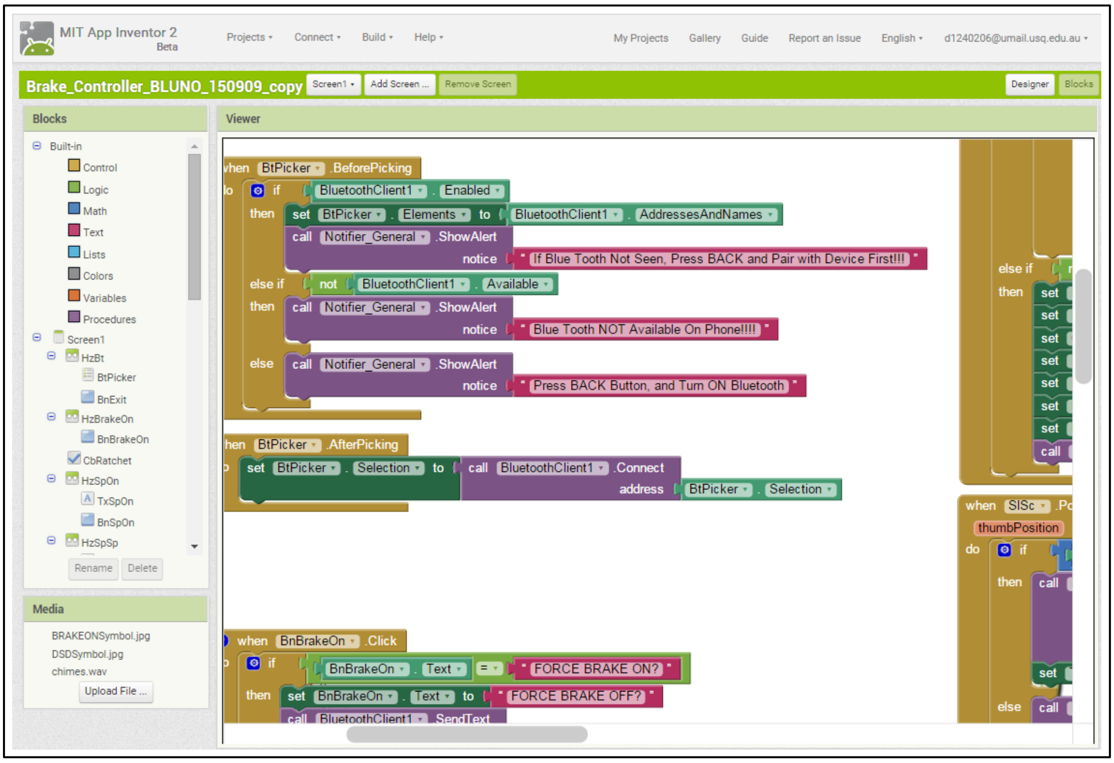


Figure 6-18: App Inventor Designer View

The previous figure shows the designer layout, which has been built as per the design in chapter 5.

Following is an image of the blocks view:



```
vhen BtPicker .BeforePicking
lo  if  BluetoothClient1 . Enabled
    then  set BtPicker . Elements to  BluetoothClient1 . AddressesAndNames
          call Notifier_General .ShowAlert
                            notice  " If Blue Tooth Not Seen, Press BACK and Pair with Device First!!! "
    else if  not  BluetoothClient1 . Available
    then  call Notifier_General .ShowAlert
                            notice  " Blue Tooth NOT Available On Phone!!!! "
    else  call Notifier_General .ShowAlert
                            notice  " Press BACK Button, and Turn ON Bluetooth "

hen BtPicker .AfterPicking
o  set BtPicker . Selection to  call BluetoothClient1 .Connect
                                              address  BtPicker . Selection

when BnBrakeOn .Click
   if  BnBrakeOn . Text  =  " FORCE BRAKE ON? "
   then  set BnBrakeOn . Text to  " FORCE BRAKE OFF? "
         call BluetoothClient1 .SendText

else if
then  set
      set
      set
      set
      set
      set
      set
      call

when SlSc .Po
  thumbPosition
do  if
    then  call
          set
    else  call
```

Figure 6-19: App Inventor Blocks View

In the following sections, the code will be described first, followed by an image of the relevant code.

6.4.1 Local Variables

All local variables have been declared in the ‘Designer’ view and are shown in brackets within the below figure.

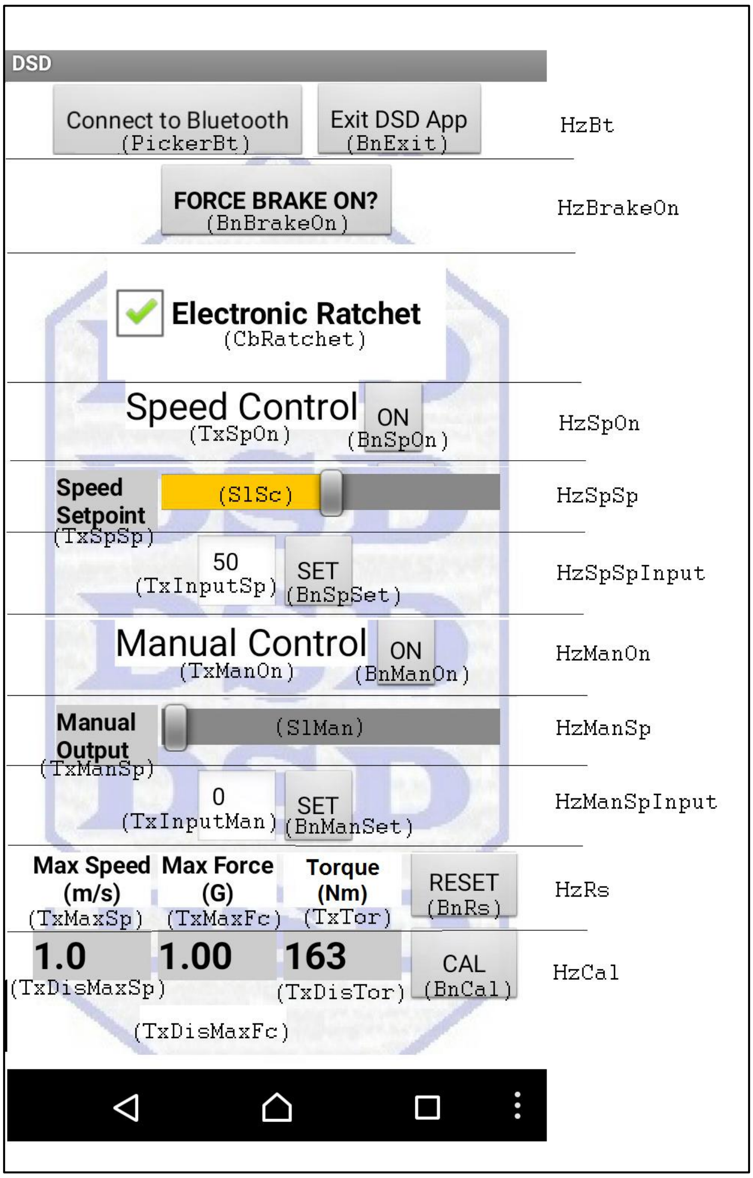


Figure 6-20: Phone Application User Interface with Variables

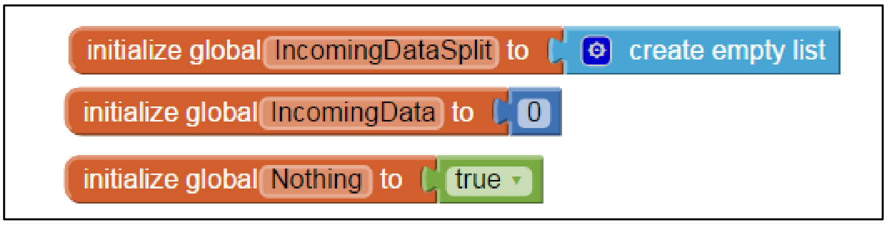
Table 6-3: Variable Naming Convention

Variable Type		Description 1		Description 2	
Text	**Comment**	**Text**	**Comment**	**Text**	**Comment**
Picker	List Picker	Dis	Display	On	On/Off
Sl	Slider	Ratchet	Ratchet	Sp	Setpoint
Bn	Button	Exit	Exit	Set	Set Value
Tx	Text Box	Bt	BlueTooth	Fc	Force
TxInput	Text Box for User Input	Sp	Speed	Tor	Torque
TxDis	Text Box for Displaying	Input	Input		
Cb	Check Box	Man	Manual Mode		
Hz	Horizontal Group	Max	Maximum Value		
		Rs	Reset		
		Cal	Calibrate		
		Tor	Torque		

The variables follow the following naming convention. Note that the middle or end parts of the tags are not always present. Refer to Appendix F for a complete local variable listing.

6.4.2 Initialisation of global variables

The three global variables declared in the 'blocks' builder is shown below. They will be explained further in the code explanations.

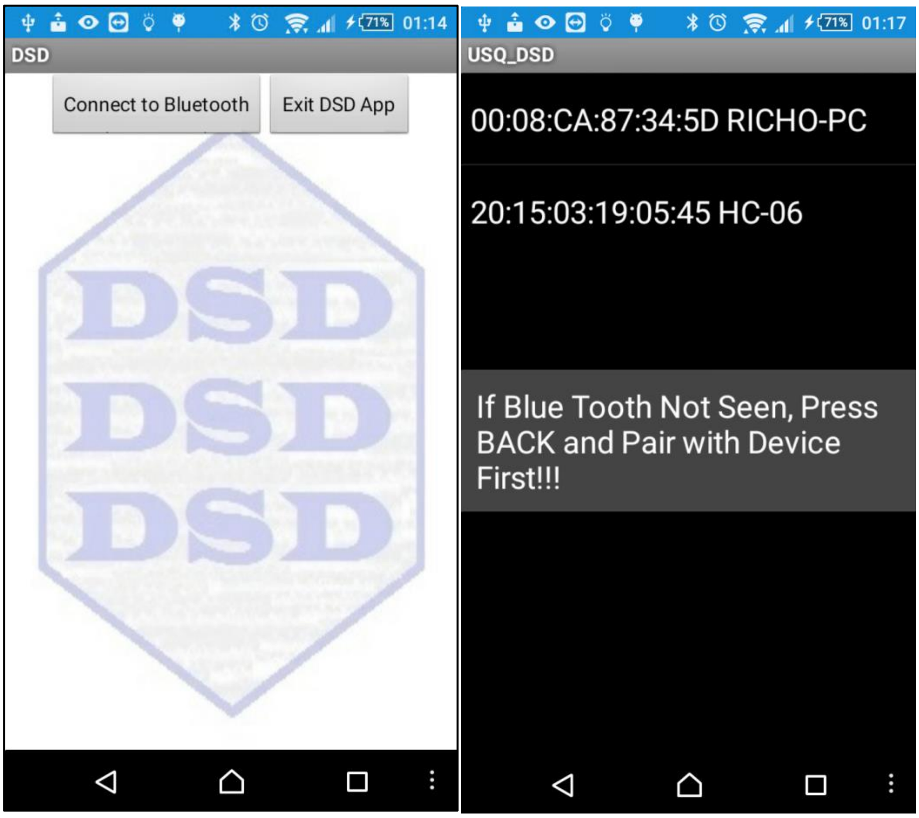


```
initialize global IncomingDataSplit to create empty list
initialize global IncomingData to 0
initialize global Nothing to true
```

Figure 6-21: Global Variables

6.4.3 Connection to Bluetooth

The only buttons displayed prior to Bluetooth being connected are 'Exit DSD app' and 'Connect to Bluetooth':



00:08:CA:87:34:5D RICHO-PC

20:15:03:19:05:45 HC-06

If Blue Tooth Not Seen, Press BACK and Pair with Device First!!!

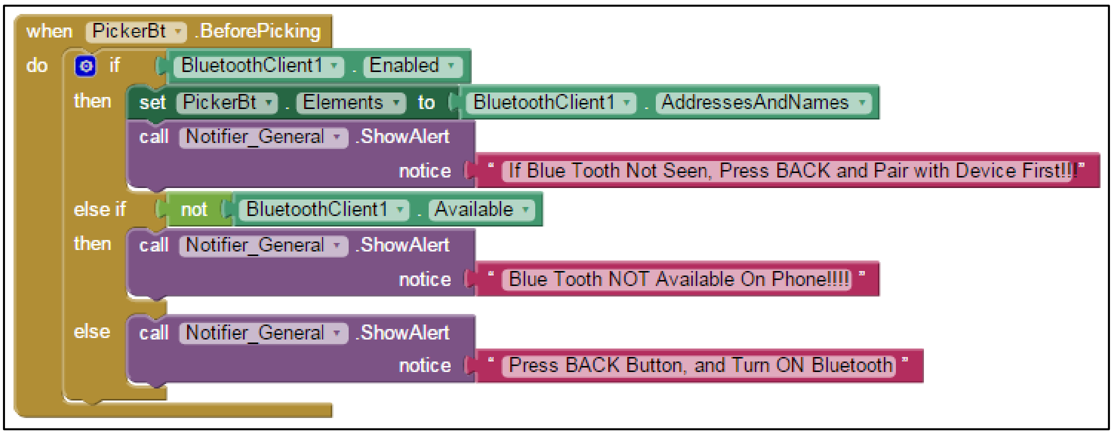
Figure 6-22: Opening Screen and List Picker for Bluetooth

A list picker is used to enable a choice of Bluetooth paired devices to be chosen. The Bluetooth device must have previously been paired for it to appear in the list.

Once the button is pressed, if the Bluetooth on the phone is enabled, then the phone will display the addresses and names of Bluetooth paired devices. A notifier is also displayed stating “If Bluetooth NOT seen, Press BACK and pair with Device First”. This is a reminder that Bluetooth devices need to be paired prior to connection.

If Bluetooth connection is not available, then an alert states “Bluetooth NOT available on Phone”.

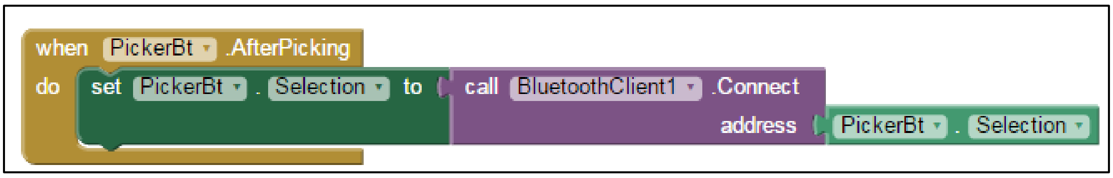
The final else statement means that the Bluetooth is installed on the phone, however not enabled, so the alert states “Press BACK Button and Turn ON Bluetooth”.



```
when PickerBt .BeforePicking
do  if     BluetoothClient1 . Enabled
    then   set PickerBt . Elements to  BluetoothClient1 . AddressesAndNames
           call Notifier_General .ShowAlert
                                notice  " If Blue Tooth Not Seen, Press BACK and Pair with Device First!!! "
    else if  not  BluetoothClient1 . Available
    then   call Notifier_General .ShowAlert
                                notice  " Blue Tooth NOT Available On Phone!!!! "
    else   call Notifier_General .ShowAlert
                                notice  " Press BACK Button, and Turn ON Bluetooth "
```

Figure 6-23: Bluetooth Connection Prior to Picking

Once the Bluetooth item is selected, the Bluetooth Client is connected to the DSD Bluetooth address.



```
when PickerBt .AfterPicking
do  set PickerBt . Selection to  call BluetoothClient1 .Connect
                                               address  PickerBt . Selection
```

Figure 6-24: Bluetooth Connection After Picking

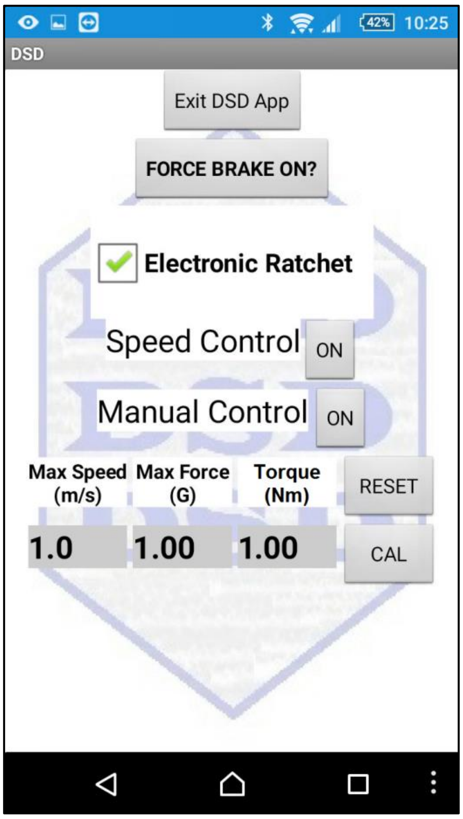
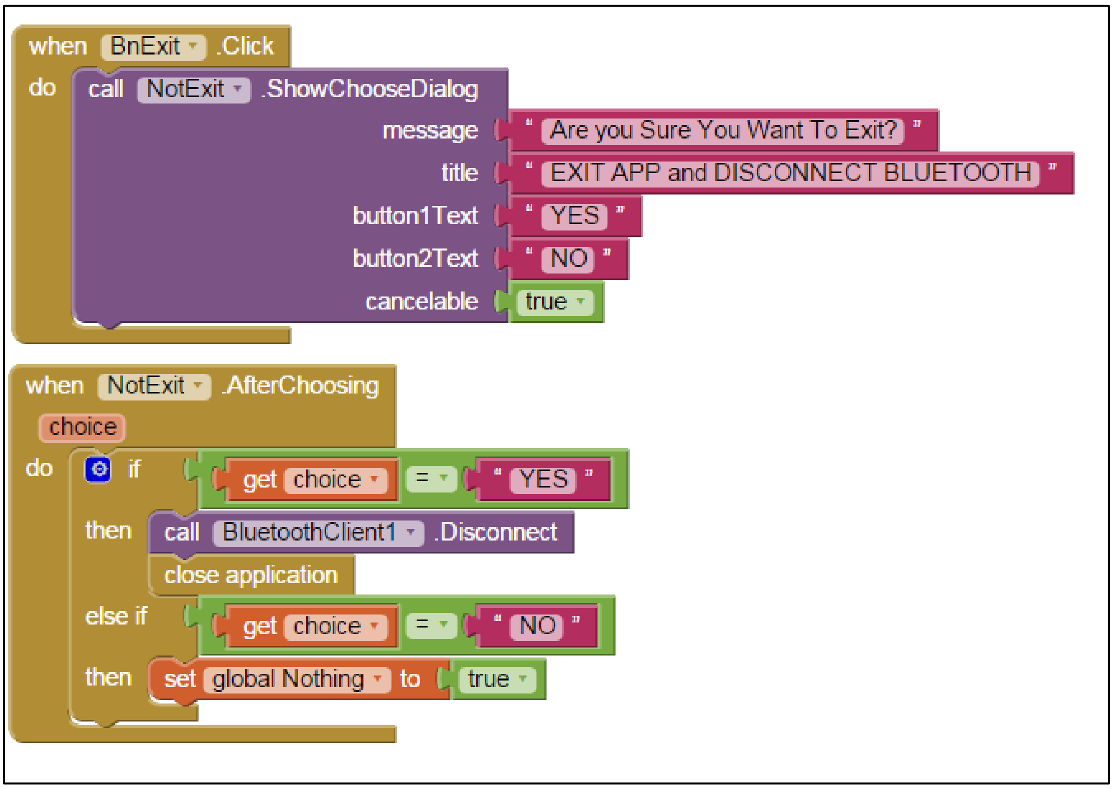


Figure 6-25: Display once connected

6.4.4 Exiting the Application

The exit button stops the application. The back button has been disabled because if pressed it closes the application and disconnects the Bluetooth. The exit button is the only way to stop the application. Bluetooth is also disconnected on exit and an option to not exit can also be selected.

The below figure shows the code for when the exit button is clicked, and the actions taken. The lower code either exits the application and closes the Bluetooth connection, or does nothing depending upon which button is pressed.

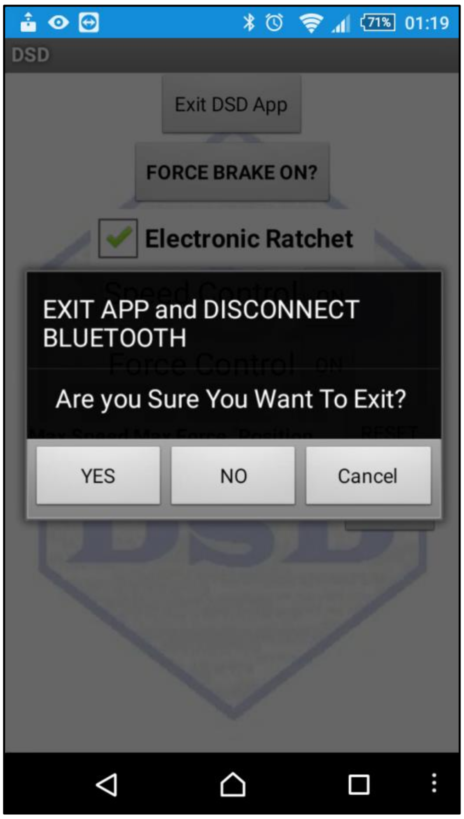


```
when BnExit .Click
do  call NotExit .ShowChooseDialog
                          message  " Are you Sure You Want To Exit? "
                            title  " EXIT APP and DISCONNECT BLUETOOTH "
                      button1Text  " YES "
                      button2Text  " NO "
                       cancelable  true

when NotExit .AfterChoosing
  choice
do  if      get choice = " YES "
    then    call BluetoothClient1 .Disconnect
            close application
    else if get choice = " NO "
    then    set global Nothing to true
```

Figure 6-26: Exit Button

The phone application notification is displayed below



EXIT APP and DISCONNECT BLUETOOTH

Are you Sure You Want To Exit?

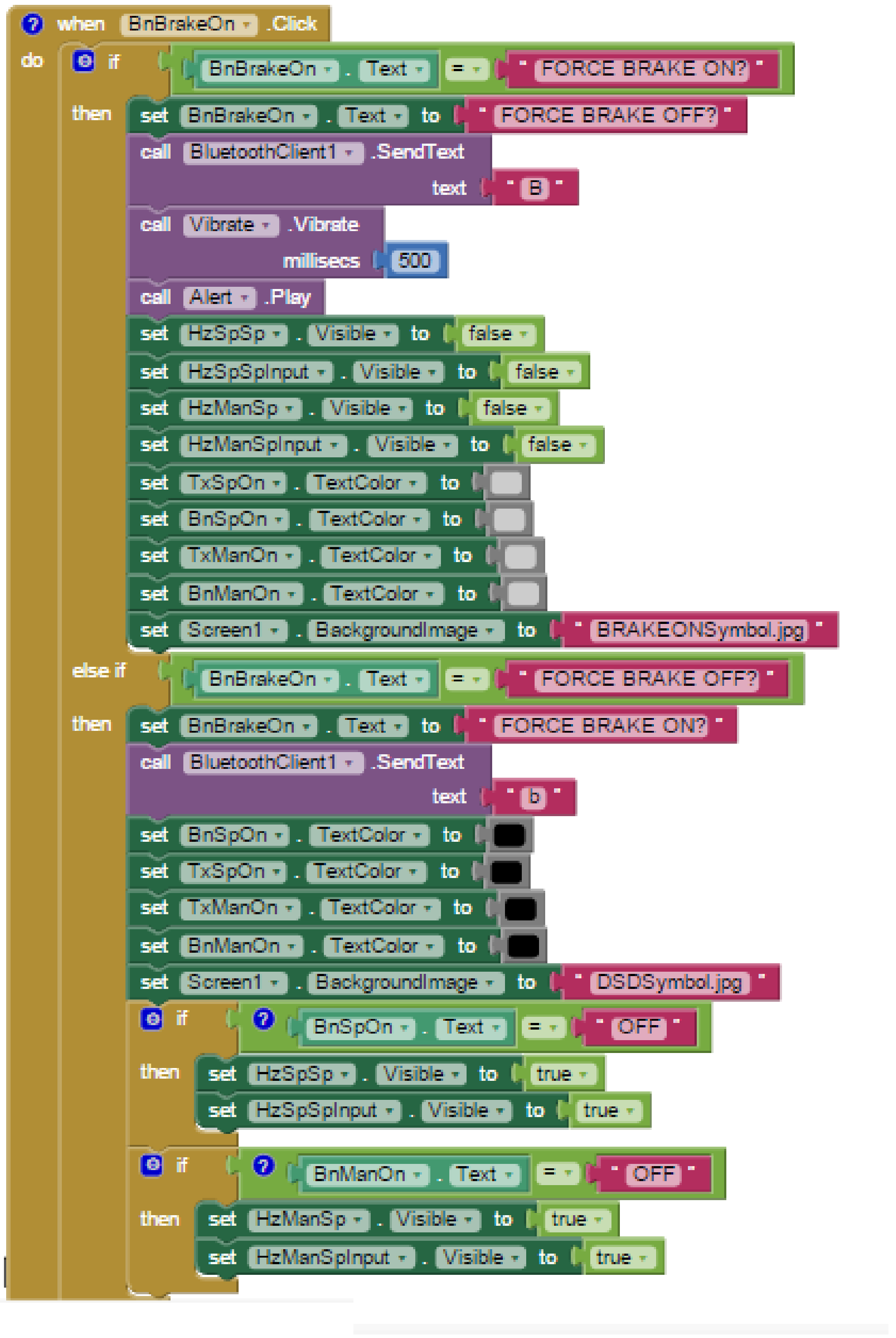
Figure 6-27: Exit Application Pop-up

6.4.5 Brake On Override

Once a connection is made, the brake can be manually overridden any time via the ‘Force Brake On?’ button. Pressing it will play the alert beep, change the background image to a red and yellow image and vibrate the phone to alert the user that they have just manually overridden the brake. The text is then changed to ‘Force Brake Off?’ and a ‘B’ is sent via Bluetooth to tell the Arduino to turn the brake on.

The code then looks at the text to see if the brake is on or off, as the button text is changed depending upon the state. If the brake is on and the button is pressed, then a lower case ‘b’ is sent to the phone to tell the Arduino to turn the brake off (go back to the last state it was in).

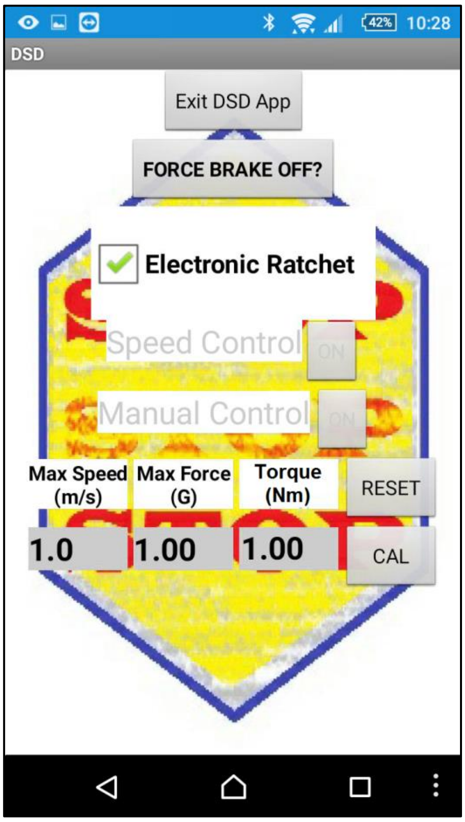
When the ‘Force Brake On?’ button is pressed all the other input boxes become invisible and the Speed and Manual mode selection buttons become light grey.



```
when BnBrakeOn .Click
do  if    BnBrakeOn . Text = " FORCE BRAKE ON? "
    then  set BnBrakeOn . Text to " FORCE BRAKE OFF? "
          call BluetoothClient1 .SendText
                                      text " B "
          call Vibrate .Vibrate
                        millisecs 500
          call Alert .Play
          set HzSpSp . Visible to false
          set HzSpSpInput . Visible to false
          set HzManSp . Visible to false
          set HzManSpInput . Visible to false
          set TxSpOn . TextColor to ▢
          set BnSpOn . TextColor to ▢
          set TxManOn . TextColor to ▢
          set BnManOn . TextColor to ▢
          set Screen1 . BackgroundImage to " BRAKEONSymbol.jpg "
    else if  BnBrakeOn . Text = " FORCE BRAKE OFF? "
    then  set BnBrakeOn . Text to " FORCE BRAKE ON? "
          call BluetoothClient1 .SendText
                                      text " b "
          set BnSpOn . TextColor to ■
          set TxSpOn . TextColor to ■
          set TxManOn . TextColor to ■
          set BnManOn . TextColor to ■
          set Screen1 . BackgroundImage to " DSDSymbol.jpg "
          if    BnSpOn . Text = " OFF "
          then  set HzSpSp . Visible to true
                set HzSpSpInput . Visible to true
          if    BnManOn . Text = " OFF "
          then  set HzManSp . Visible to true
                set HzManSpInput . Visible to true
```

Figure 6-28: Brake On Button

Following is the phones display while the brake is pressed



☑ Electronic Ratchet

Max Speed (m/s)	Max Force (G)	Torque (Nm)
1.0	1.00	1.00

Figure 6-29: Brake On Display

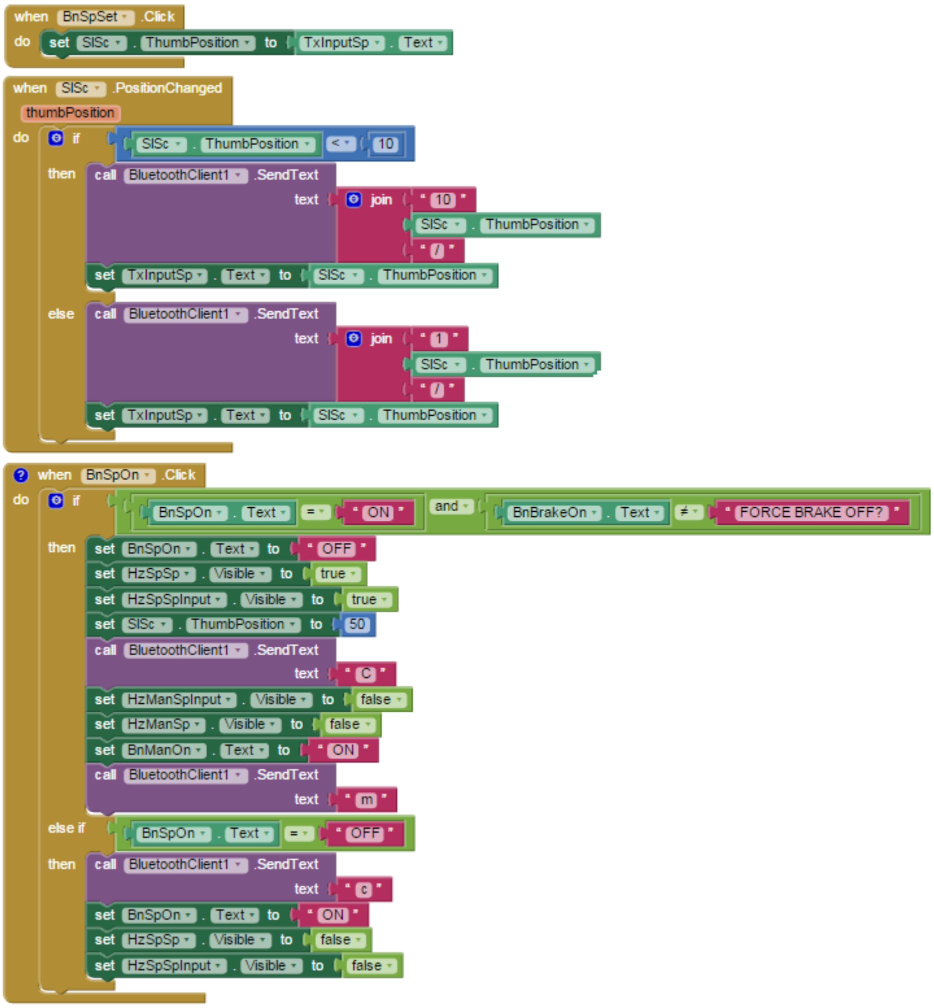
6.4.6 Speed Control Mode

Speed control mode is the automatic control. In this mode, whenever the speed is exceeded, the brake will control the braking via PID control to reduce the speed to below the set-point. The set-point of 0-100 % corresponds to 0-3 m/s.

If the brake is not in override mode, then the speed control can be switched on. If the manual control is on at the time then it will get turned off.

Once the speed control is switched on, then the speed set-point automatically gets set to a 50 % default position. This is a safe start position and ensures that braking does not occur immediately due to a zero speed set-point A ‘C’ is sent to the Arduino to tell the Arduino that the Speed control is on and the set-point entry components are made visible. The slider bar allows an easy touch screen adjustment, while the text entry allows an exact set-point to be entered. Once the data is entered into the text box, the ‘Set’ button writes the data to the slider position to ensure that the slider reflects the set-point entered.

The set-point data is then sent to the Arduino via Bluetooth, the code puts a leading 1 on the data and also places a ‘/’ at the end of the text string. The ‘1’ signifies to the Arduino that the data is for the Speed Set-point and the ‘/’ signifies the end of the speed set-point.



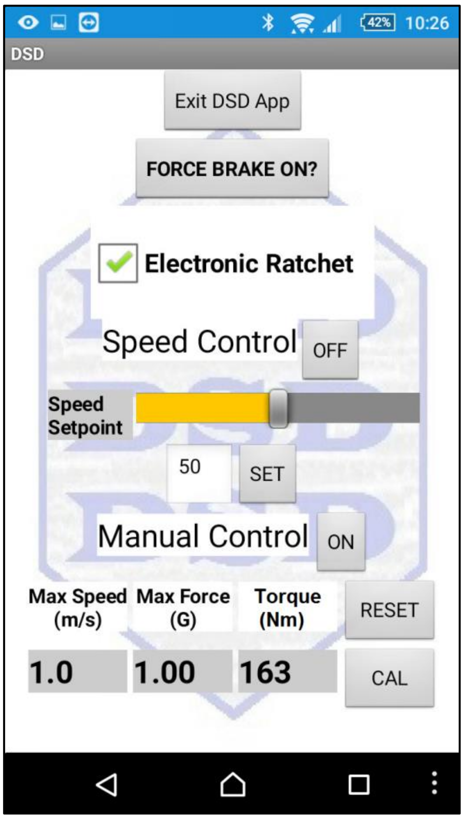
```
when BnSpSet .Click
do  set SlSc . ThumbPosition to TxInputSp . Text

when SlSc .PositionChanged
  thumbPosition
do  if    SlSc . ThumbPosition < 10
    then  call BluetoothClient1 .SendText
                          text  join  " 10 "
                                      SlSc . ThumbPosition
                                      " / "
          set TxInputSp . Text to SlSc . ThumbPosition
    else  call BluetoothClient1 .SendText
                          text  join  " 1 "
                                      SlSc . ThumbPosition
                                      " / "
          set TxInputSp . Text to SlSc . ThumbPosition

? when BnSpOn .Click
do  if      BnSpOn . Text = " ON "  and  BnBrakeOn . Text ≠ " FORCE BRAKE OFF? "
    then    set BnSpOn . Text to " OFF "
            set HzSpSp . Visible to true
            set HzSpSpInput . Visible to true
            set SlSc . ThumbPosition to 50
            call BluetoothClient1 .SendText
                            text  " C "
            set HzManSpInput . Visible to false
            set HzManSp . Visible to false
            set BnManOn . Text to " ON "
            call BluetoothClient1 .SendText
                            text  " m "
    else if BnSpOn . Text = " OFF "
    then    call BluetoothClient1 .SendText
                            text  " c "
            set BnSpOn . Text to " ON "
            set HzSpSp . Visible to false
            set HzSpSpInput . Visible to false
```

Figure 6-30: Speed Control Blocks

Below is the phone application view when the Speed Control is turned on.



☑ Electronic Ratchet

Speed Control OFF

Speed Setpoint 50

Manual Control ON

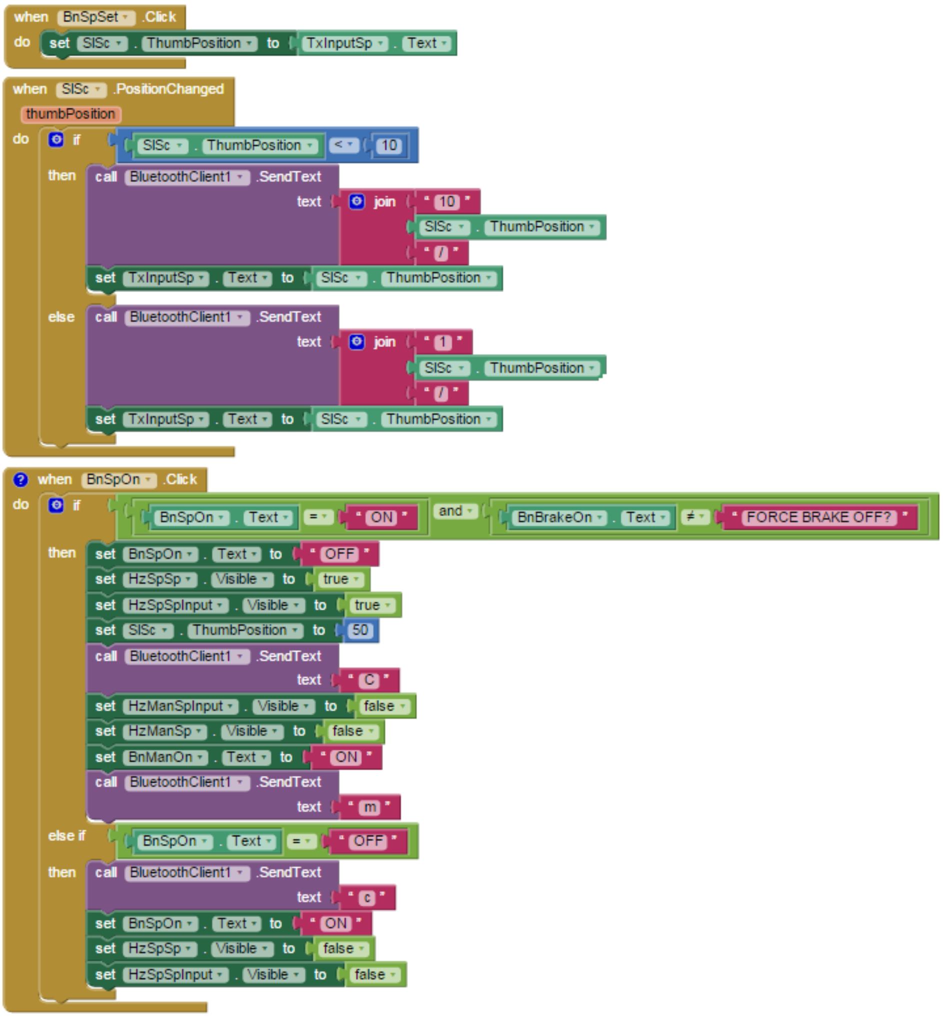
Max Speed (m/s)	Max Force (G)	Torque (Nm)
1.0	1.00	163

Figure 6-31: Speed Control Display

6.4.7 Manual Control Mode

The Manual control mode has the same interface functionality as the Speed Control. The difference being that an ‘M’ is sent to the Arduino rather than a ‘C’ to indicate that the manual mode is on. Other differences are that the set-point default is 0 and the analogue value sent has a leading ‘2’ rather than a ‘1’.

Manual mode is used to send a manual set-point which drives the brake output. 0 is no output and 100 is full output.



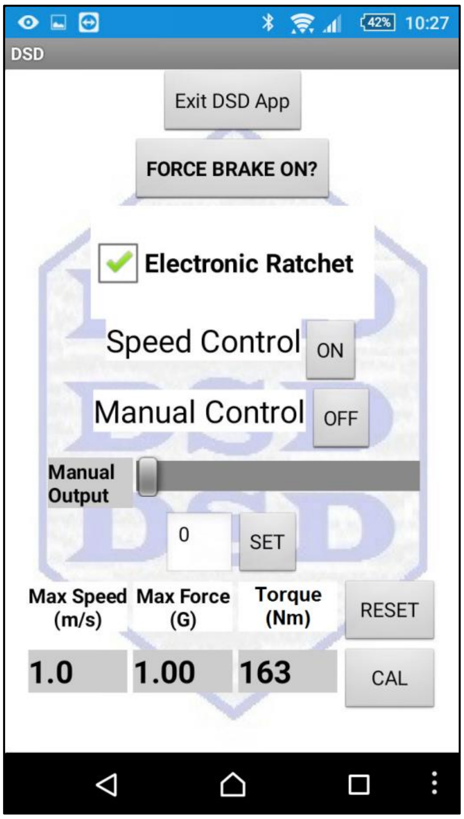
```
when BnSpSet .Click
do  set SlSc . ThumbPosition to TxInputSp . Text

when SlSc .PositionChanged
  thumbPosition
do  if   SlSc . ThumbPosition < 10
    then call BluetoothClient1 .SendText
              text  join  " 10 "
                          SlSc . ThumbPosition
                          " / "
         set TxInputSp . Text to SlSc . ThumbPosition
    else call BluetoothClient1 .SendText
              text  join  " 1 "
                          SlSc . ThumbPosition
                          " / "
         set TxInputSp . Text to SlSc . ThumbPosition

when BnSpOn .Click
do  if   BnSpOn . Text = " ON "  and  BnBrakeOn . Text ≠ " FORCE BRAKE OFF? "
    then set BnSpOn . Text to " OFF "
         set HzSpSp . Visible to true
         set HzSpSpInput . Visible to true
         set SlSc . ThumbPosition to 50
         call BluetoothClient1 .SendText
              text " C "
         set HzManSpInput . Visible to false
         set HzManSp . Visible to false
         set BnManOn . Text to " ON "
         call BluetoothClient1 .SendText
              text " m "
    else if BnSpOn . Text = " OFF "
    then call BluetoothClient1 .SendText
              text " c "
         set BnSpOn . Text to " ON "
         set HzSpSp . Visible to false
         set HzSpSpInput . Visible to false
```

Figure 6-32: Manual Control Blocks

Below is the phone application view when the Manual Control is turned on.



☑ Electronic Ratchet

Speed Control ON

Manual Control OFF

Manual Output 0

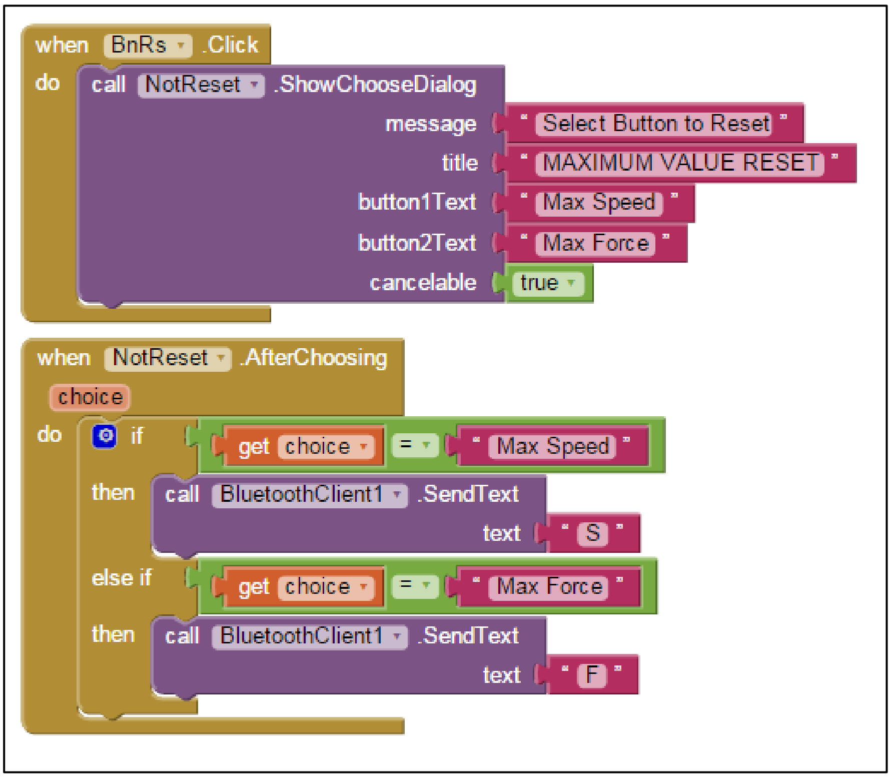
Max Speed (m/s)	Max Force (G)	Torque (Nm)
1.0	1.00	163

Figure 6-33: Manual Control Display

6.4.8 Reset Functionality

The reset button allows resetting of the maximum G-Force and maximum speed recorded. These maximums are recorded by the Arduino and sent to the phone to allow the carer to observe the maximum figures.

The resets trigger a notification which allows a selection of either ‘Max Speed’, ‘Max Force’ or to ‘Cancel’. Once a selection is made, either a ‘S’ or ‘F’ is sent via Bluetooth to the Arduino to request a reset of the maximum speed or force recorded.

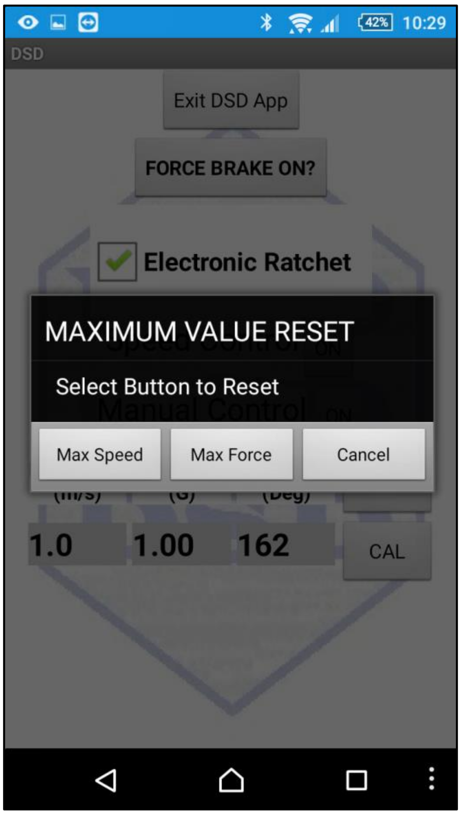


```
when BnRs .Click
do  call NotReset .ShowChooseDialog
                        message    " Select Button to Reset "
                          title    " MAXIMUM VALUE RESET "
                    button1Text    " Max Speed "
                    button2Text    " Max Force "
                     cancelable    true

when NotReset .AfterChoosing
  choice
do  if      get choice = " Max Speed "
    then    call BluetoothClient1 .SendText
                                  text  " S "
    else if get choice = " Max Force "
    then    call BluetoothClient1 .SendText
                                  text  " F "
```

Figure 6-34: Reset Button

The phone display shows the following notification when the button is pressed.



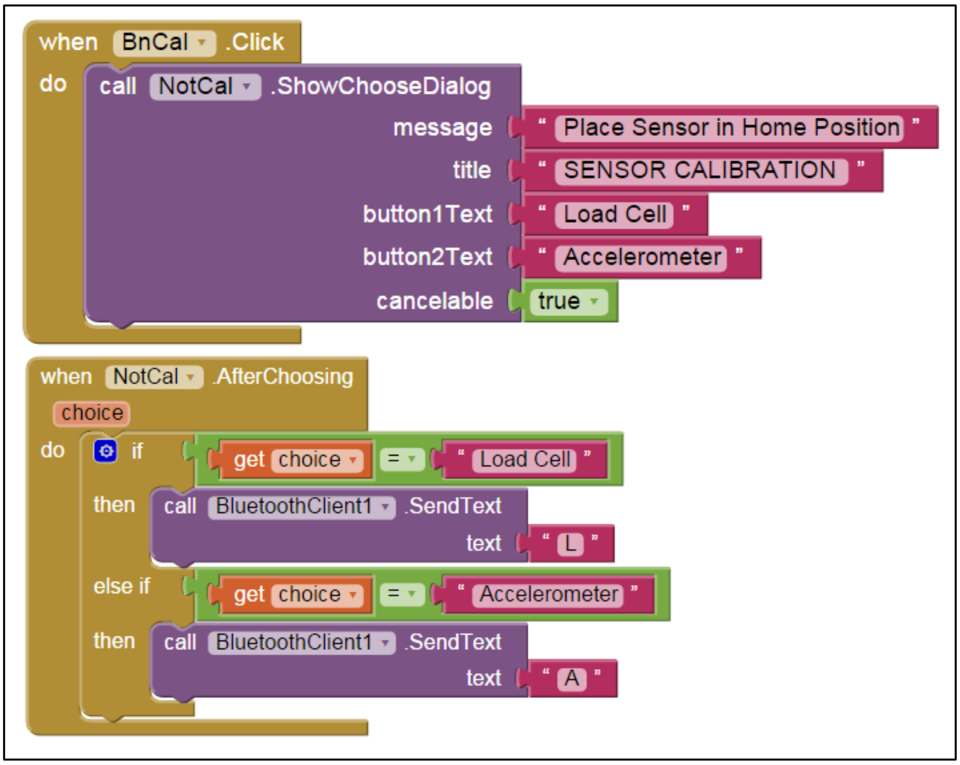
MAXIMUM VALUE RESET

Select Button to Reset

Figure 6-35: Reset Button Display

6.4.9 Calibration Functionality

Calibration of both the accelerometer and the strain gauge may be necessary. The calibrate function on both of these sensors is really a zero offset adjustment rather than a calibration, as no span is adjusted for. This calibration is acceptable, because they should read either 1.0 g for the accelerometer when still, or 0 N·m for the strain gauge when under no strain.

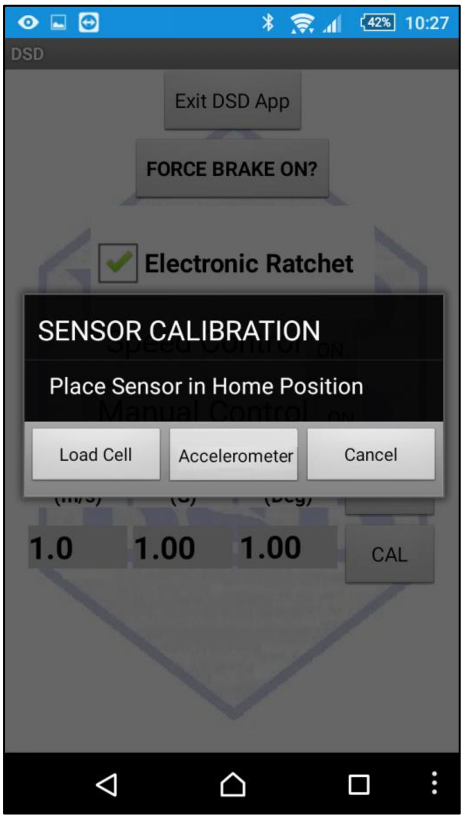


```
when BnCal .Click
do  call NotCal .ShowChooseDialog
                          message  " Place Sensor in Home Position "
                            title  " SENSOR CALIBRATION "
                      button1Text  " Load Cell "
                      button2Text  " Accelerometer "
                       cancelable  true

when NotCal .AfterChoosing
  choice
do  if       get choice = " Load Cell "
    then     call BluetoothClient1 .SendText
                                  text  " L "
    else if  get choice = " Accelerometer "
    then     call BluetoothClient1 .SendText
                                  text  " A "
```

Figure 6-36: Calibration Button

The phone display shows the following notification when the button is pressed.



SENSOR CALIBRATION

Place Sensor in Home Position

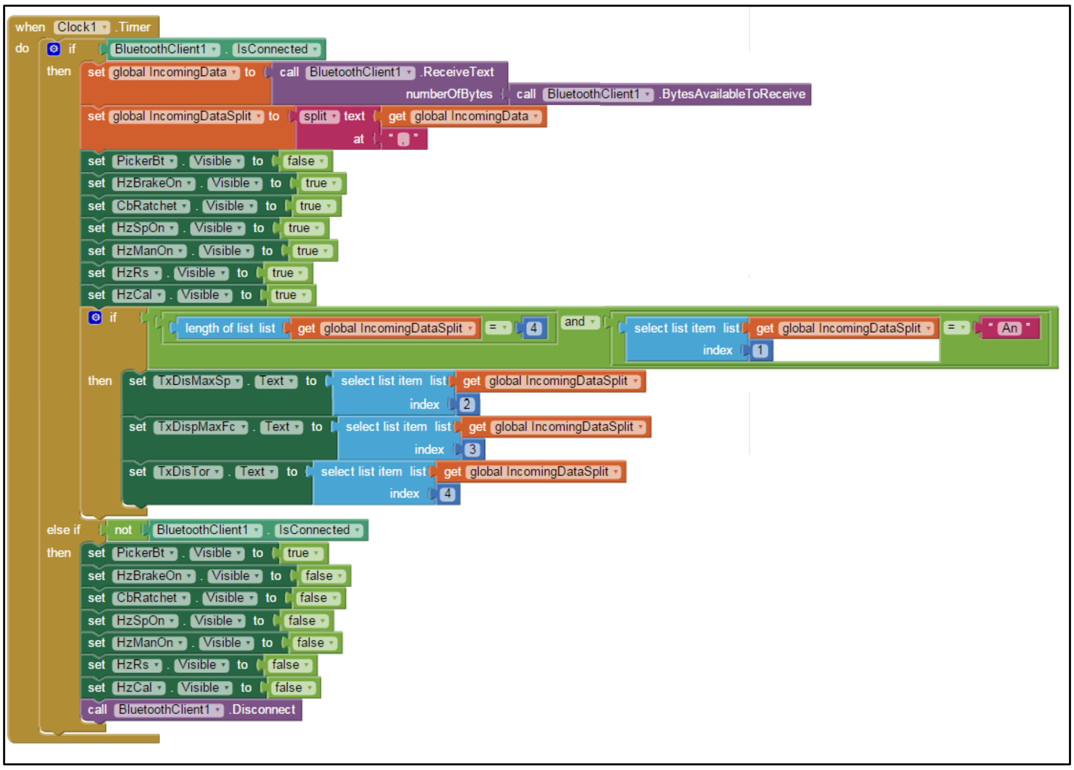
Figure 6-37: Calibration Button Display

6.4.10 Updates every second

A one second clock triggers the phone to look for data over the Bluetooth link. The data being received by the phone is a set of analogue values representing the maximum speed, maximum force and the torque. These values are sent over in a specific format. The format begins with a ‘An,’ followed by the 3 analogue values separated by comma’s.

The code looks to see if the Bluetooth connection is on and if so, stores the bytes from the Bluetooth in the global variable ‘IncomingData’. This incoming data is stored in separate bytes split by the commas and stored in ‘IncomingDataSplit’ global variable. A check is completed prior to placing the variables in their respective positions. If the length of the list is 4 and the first item in the list is ‘An’, then the last three items in the list are stored in the appropriate variables.

From the display, a check is made of the Bluetooth connection and if connected, ensures that all the buttons are displayed except for the Bluetooth connection button. If the Bluetooth connection is lost, then these buttons are made invisible.



```
when Clock1 .Timer
do  if  BluetoothClient1 . IsConnected
    then  set global IncomingData to  call BluetoothClient1 .ReceiveText
                                                  numberOfBytes  call BluetoothClient1 .BytesAvailableToReceive
          set global IncomingDataSplit to  split text  get global IncomingData
                                                   at  " , "
          set PickerBt . Visible to false
          set HzBrakeOn . Visible to true
          set CbRatchet . Visible to true
          set HzSpOn . Visible to true
          set HzManOn . Visible to true
          set HzRs . Visible to true
          set HzCal . Visible to true
          if  length of list list  get global IncomingDataSplit  =  4  and  select list item  list  get global IncomingDataSplit  =  " An "
                                                                                       index  1
          then  set TxDisMaxSp . Text to  select list item  list  get global IncomingDataSplit
                                                          index  2
                set TxDispMaxFc . Text to  select list item  list  get global IncomingDataSplit
                                                           index  3
                set TxDisTor . Text to  select list item  list  get global IncomingDataSplit
                                                        index  4
    else if  not  BluetoothClient1 . IsConnected
    then  set PickerBt . Visible to true
          set HzBrakeOn . Visible to false
          set CbRatchet . Visible to false
          set HzSpOn . Visible to false
          set HzManOn . Visible to false
          set HzRs . Visible to false
          set HzCal . Visible to false
          call BluetoothClient1 .Disconnect
```

Figure 6-38: 1 Second Block

6.5 3D Printing

The initial design was printed and the central part of the splint, being the bearing and rotating system worked well.

The aspects that needed modifying included:

- Addition of places to mount the instruments
- The splint would slip. Modifications were made to allow bolting
- Design a box to mount the controller
- Strengthen the forearm piece

6.5.1 Position Sensor

The potentiometer needed to be mounted on the base of the bearing, with the shaft inside the bearing and the head of the potentiometer kept in a static position. The centre of the plastic bearing was modified to include a tolerance fit hole for the shaft and a slot was inserted which accepts a 1 mm strip of metal to ensure the shaft does not slip.

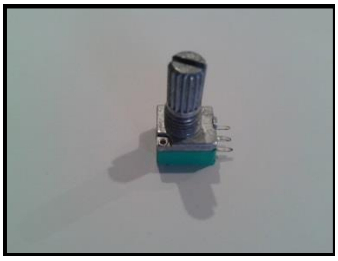


Figure 6-39: Potentiometer

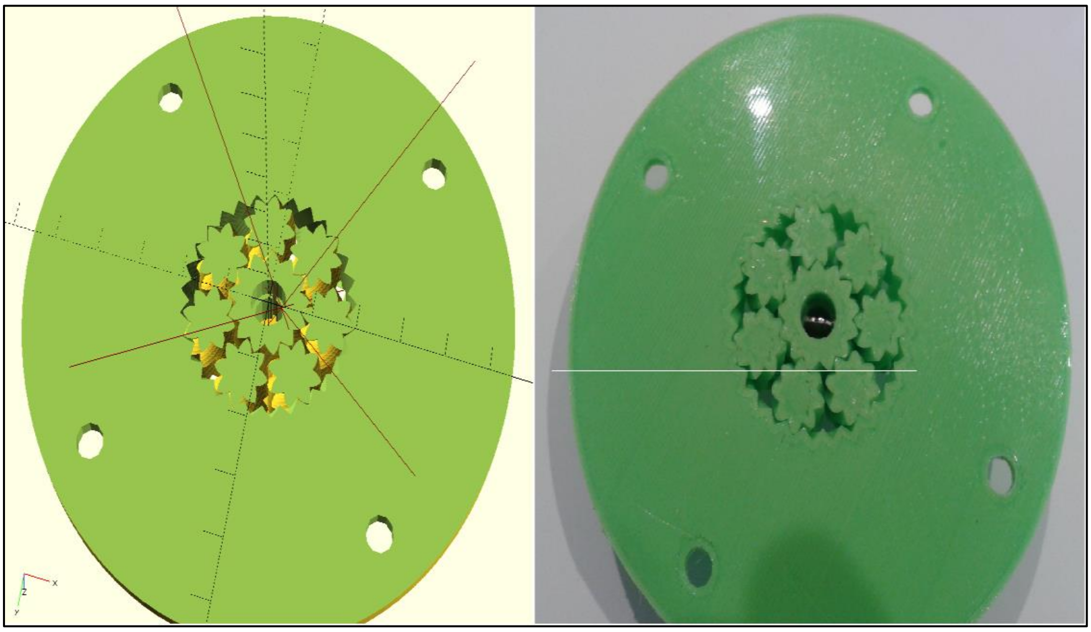


Figure 6-40: Bearing Potentiometer Insert

To ensure the head does not move, a brace was made which spans the base of the brake.

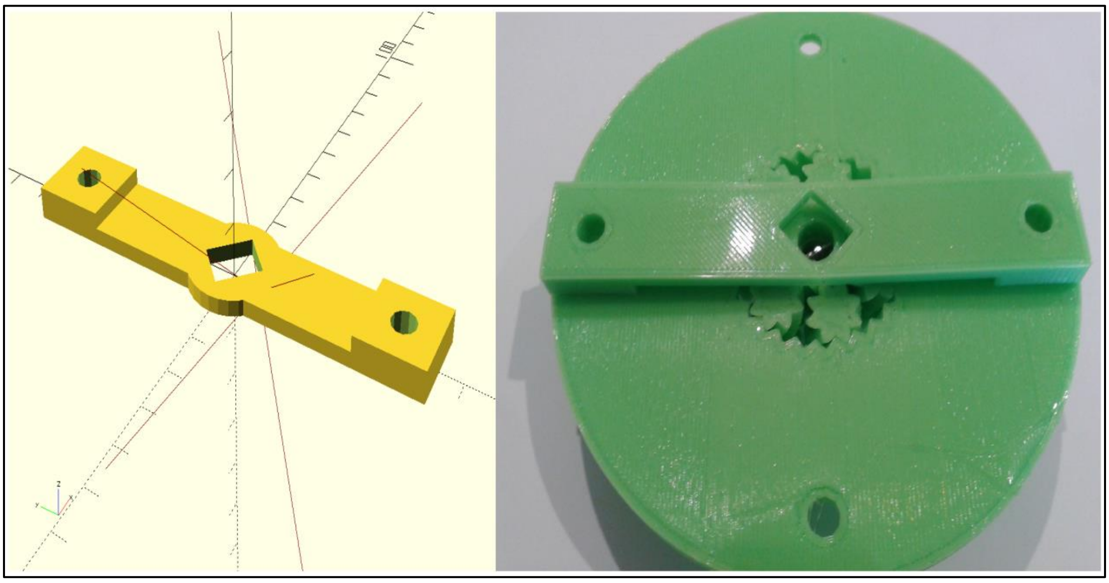


Figure 6-41: Potentiometer Bracket

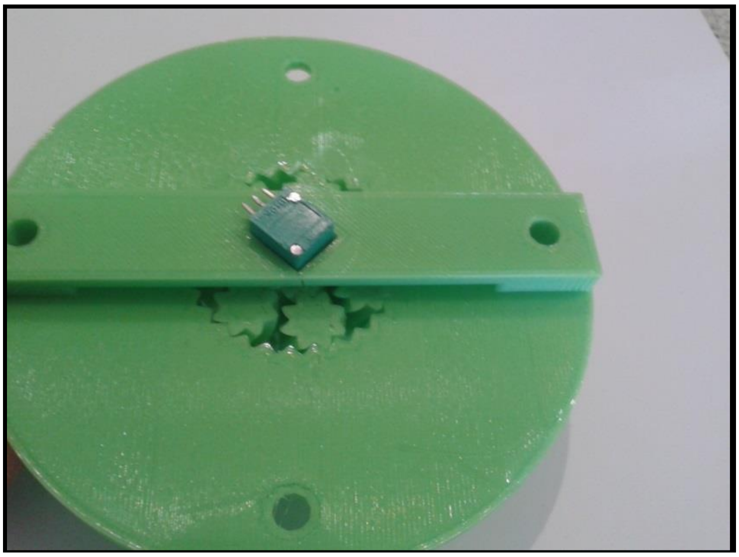


Figure 6-42: Potentiometer Fitted to Bearing Unit

6.5.2 Accelerometer

The accelerometer was mounted as far forward within the forearm piece as possible, within a recessed area. To recess the accelerometer the wires were soldered directly to the accelerometer rather utilising the plug.

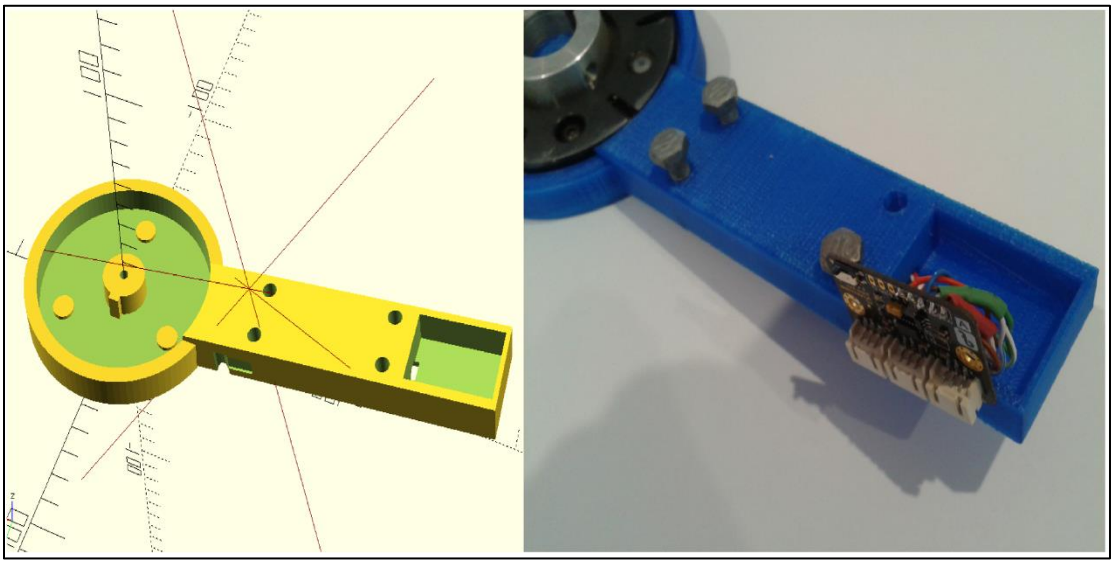


Figure 6-43: Accelerometer Fitment in Forearm Piece

The below figure shows the placement of the accelerometer electronics, the bolt addition and how the rotating part of the brake is fitted.

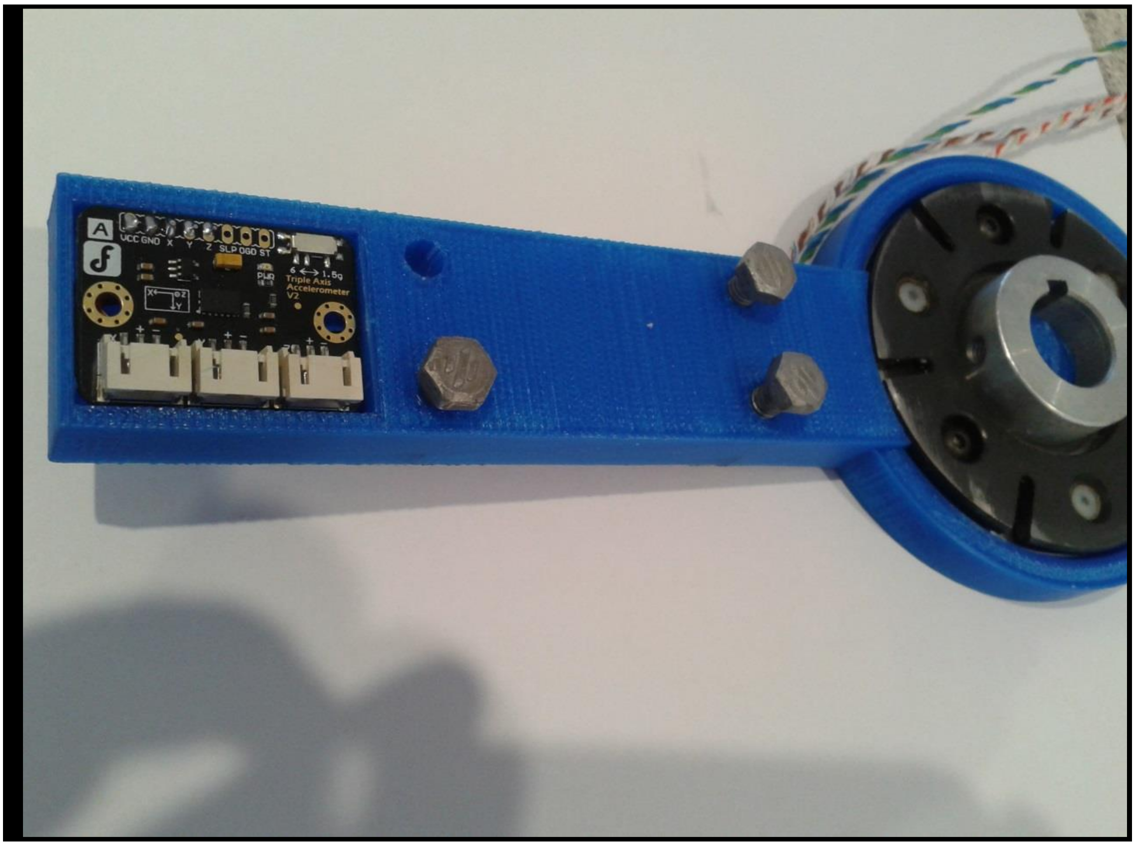


Figure 6-44: Forearm Piece with items fitted

6.5.3 Strain Gauge fitment to forearm piece

The strain gauges need to be bonded to the forearm piece. Epoxy Resin has been used as the bonding agent. Considerations in the design were to ensure:

- There was enough room for the strain gauges and the passive resistors. For the resistors to allow temperature compensation they need to be mounted with the strain gauges
- Allow wiring of the strain gauges

The figure shown below shows the design and the strain gauges assembled within the forearm piece

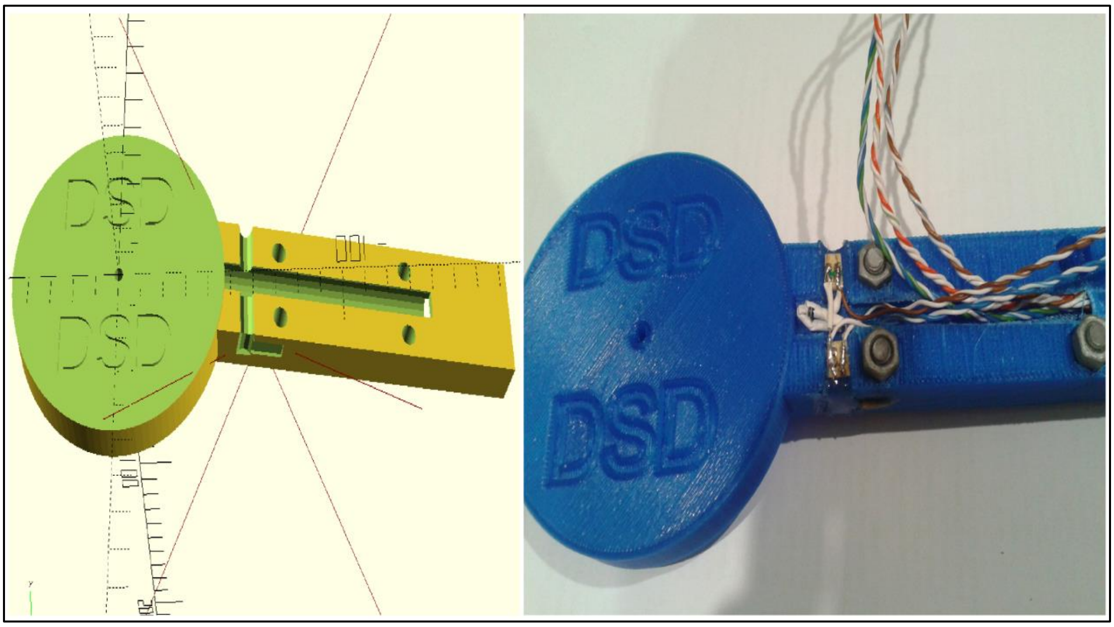


Figure 6-45: Strain Gauge Placement

The strain gauges along with the resistors and cables were glued into position. The photo above shows the strain gauges glued, however the resisters were yet to be glued in place.

The next figure shows the side view of the strain gauge epoxied in place.

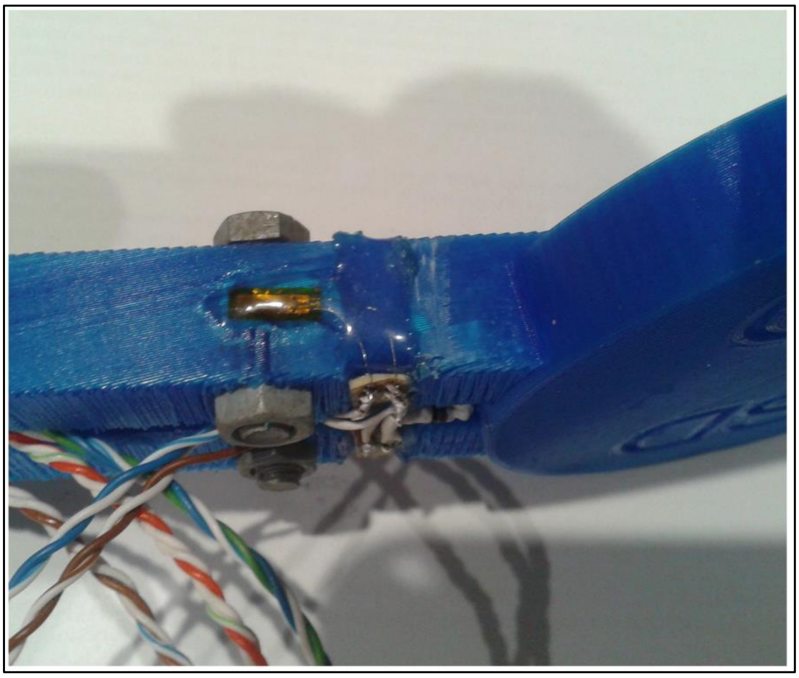


Figure 6-46: Side view of Strain Gauge

6.5.4 Arm Splints

Note that this project is not about the mechanical design but the electronic and controls of the unit. Therefore the splint component built into the unit is for the prototype to be tested and will not form part of the final design. Without it, testing could not be completed.

The images below show the initial attempt at a splint. This used PVC which was formed to the shape of the arm. This design impeded testing, as the splint slid down when the arm was attempting impact with the brake locked.

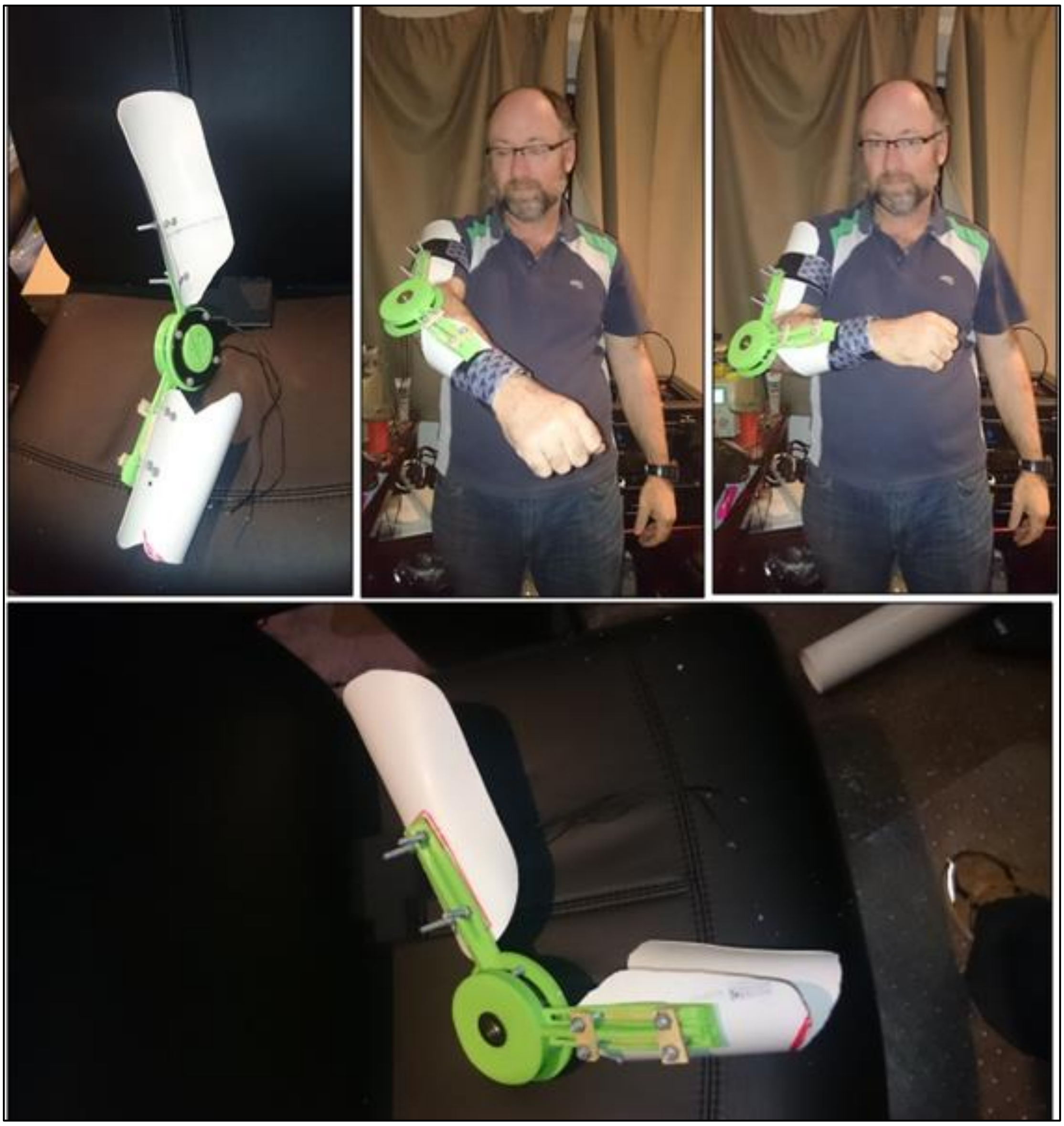


Figure 6-47: Initial PVC Splint

A better splint was created from a mesh material purchased from a splint making supplier. The material can be formed into shape after being placed in boiling water.

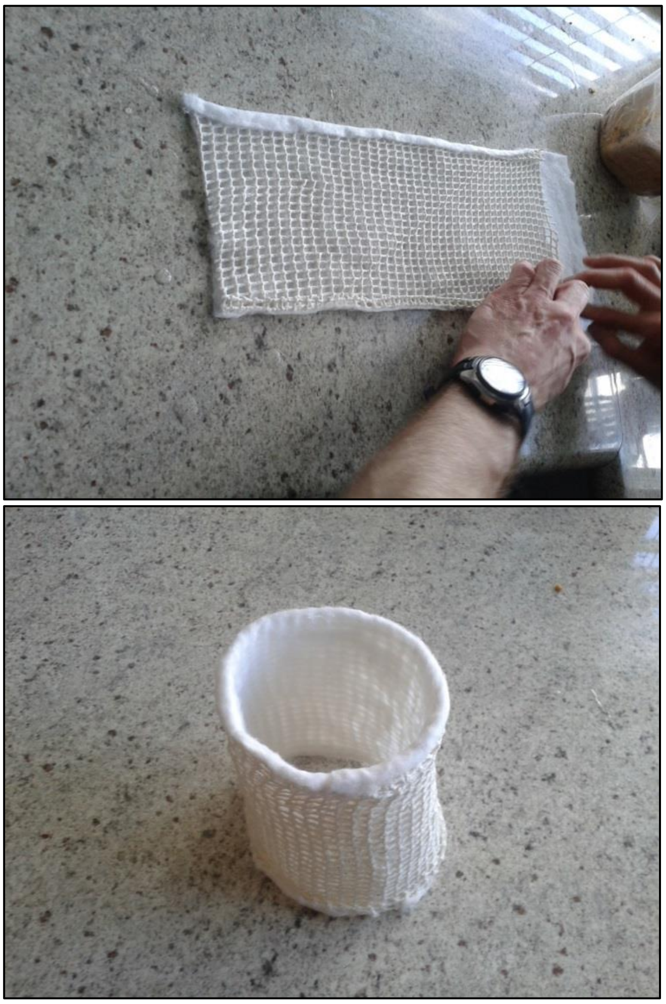


Figure 6-48: Splint Material before and after Forming

The formed splints were bolted onto the upper arm and forearm pieces. Extra 3D printed parts were designed to spread the load of the bolts and to allow a more comfortable splint.

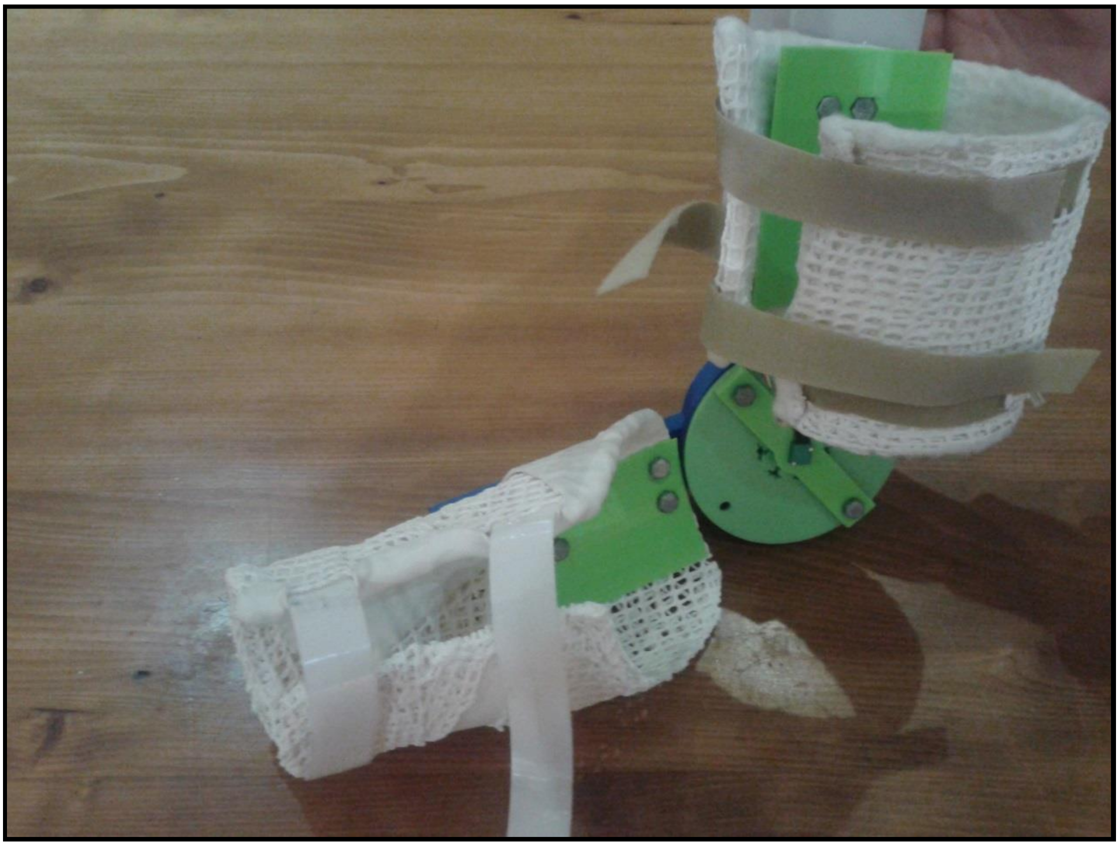


Figure 6-49: Formed Splints Mounted on DSD

The electronics were secured with Velcro to the splint, however this did not work well as the box was not secured well enough and would slip.

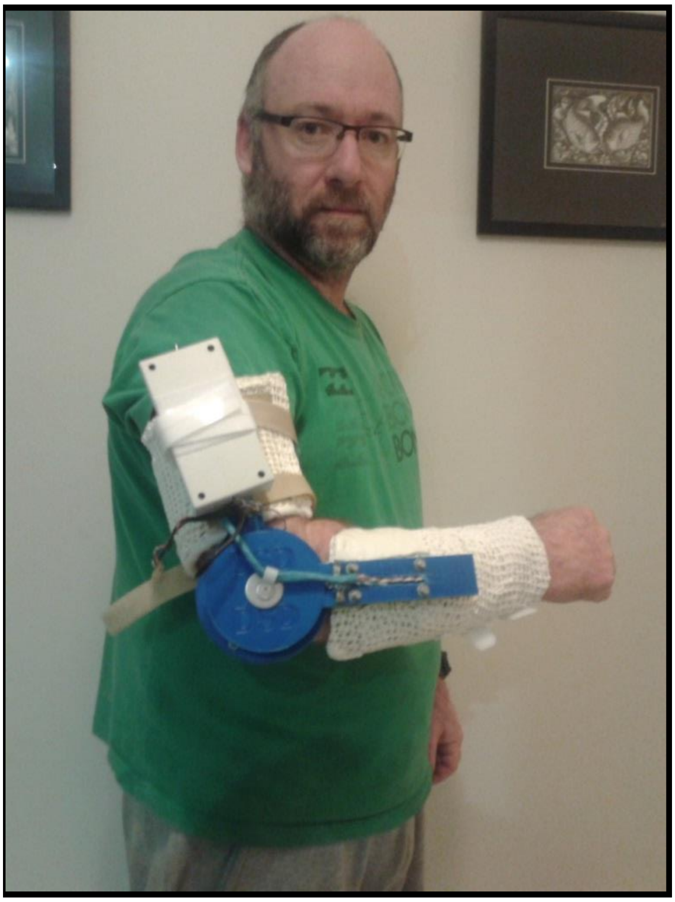


Figure 6-50: DSD with Electronic Box Secured with Velcro

6.5.5 Electronics Box

The electronics box was designed to house the battery and electronics in a separate section. Designing a box allowed the size to be customised and also allow for all securing holes to be specific for the application. Other customisations included:

- Bolt holes to line up with the splint bolts
- Built up area on lid to allow screwing of the brake drive electronics box to the lid
- Slot wide enough for all wires
- Hole for on/off switch on the side

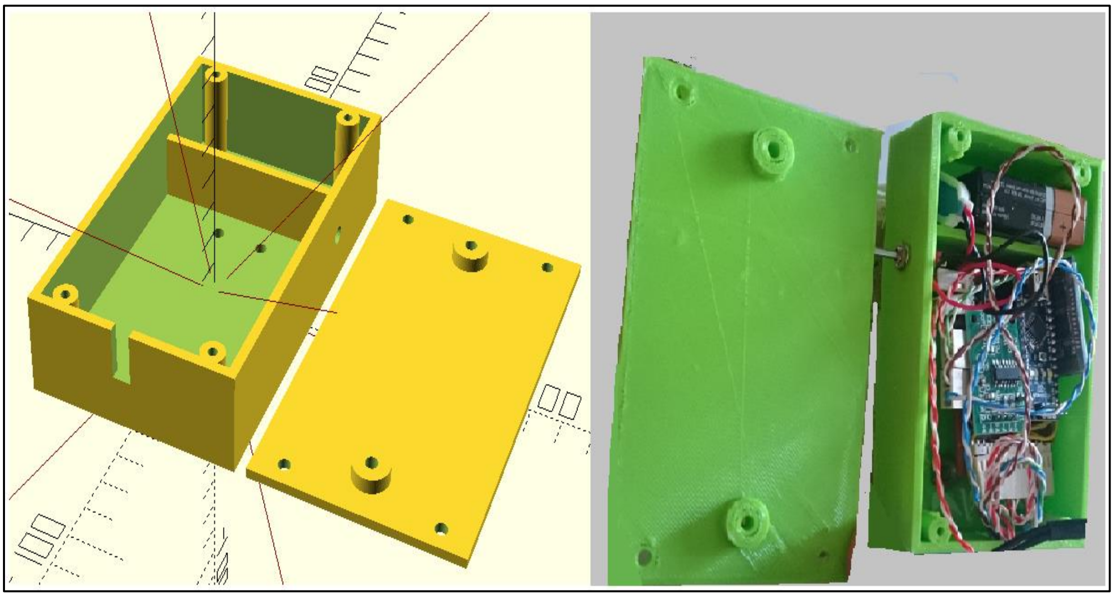


Figure 6-51: Electronic Box

The below image shows the DSD with the new electronic box fitted to the arm.

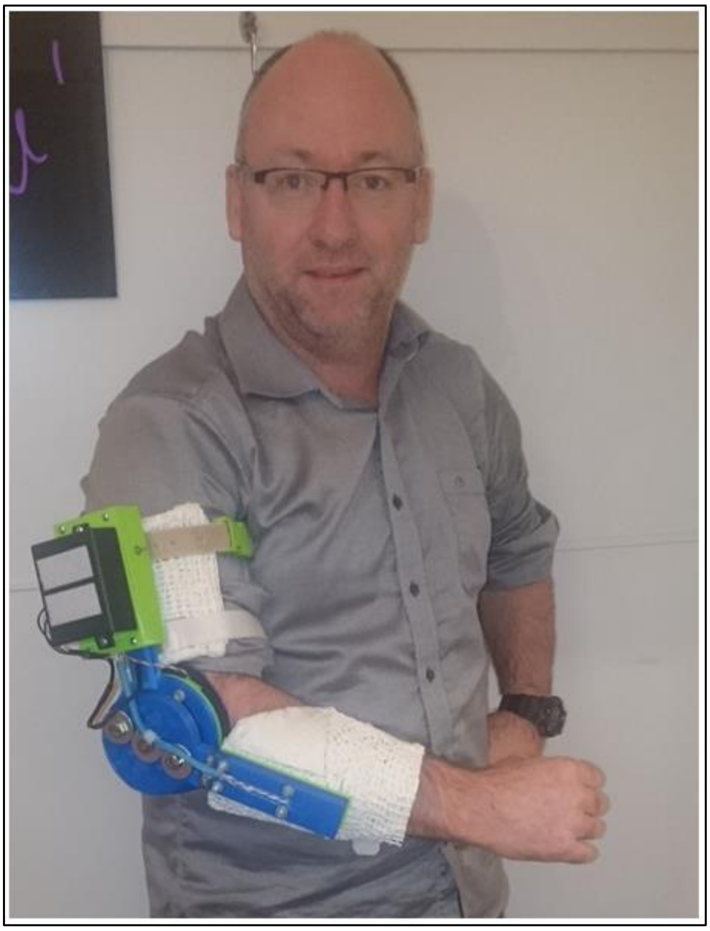


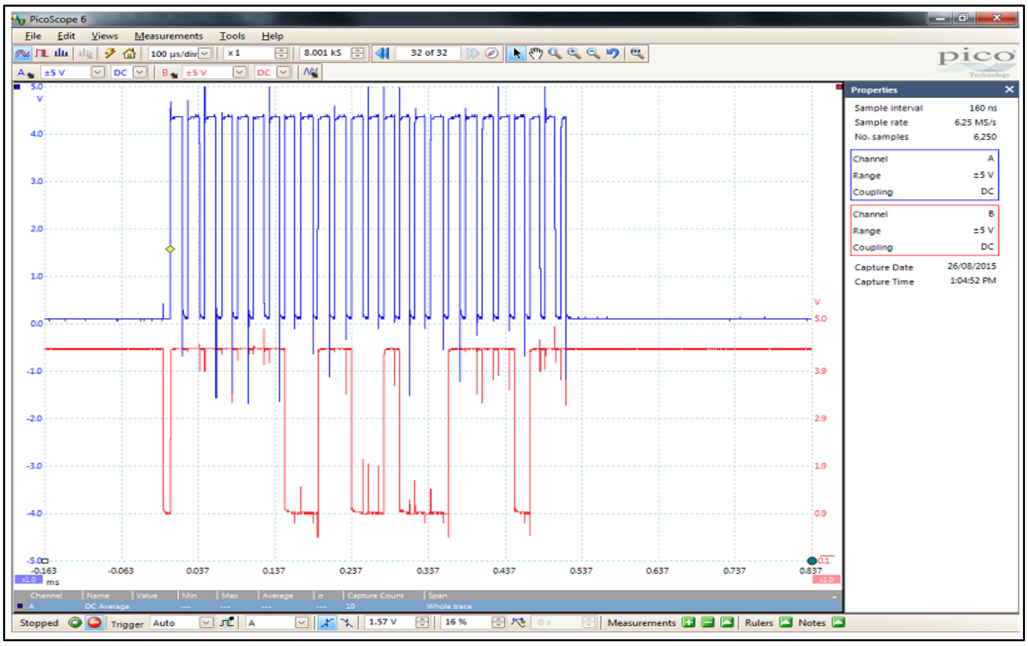
Figure 6-52: Final DSD Fitted to Arm

6.6 Combined Component Testing

Once the 3D components were complete, the device was mounted on the arm and trialled. This is the first time that the strain gauge Electronic Ratchet and speed control could be tested.

6.6.1 Torque Strain Gauge

The first test completed on the torque strain gauge was to measure the clock (PD_CLK) and data (DOUT) pulses from the HX711 strain gauge amplifier board to confirm the gain of 128 and that it was transmitting data.



Properties

Sample interval	160 ns
Sample rate	6.25 MS/s
No. samples	6,250
Channel	A
Range	±5 V
Coupling	DC
Channel	B
Range	±5 V
Coupling	DC
Capture Date	26/08/2015
Capture Time	1:04:52 PM

Channel	Name	Value	Min	Max	Average	σ	Capture Count	Span
A	DC Average		---	---	---	---	10	Whole trace

Figure 6-53: HX711 Clock pulse and Data trace

The data above was completed using an oscilloscope and shows the PD_SCK clock cycle in blue (upper trace) and the DOUT data in red (lower trace). This signal is 2's compliment with the MSB on the left hand side (Avia Semiconductor 2014).

The 25th clock cycle confirms that the HX711 gain is set to 128 and the initial data pin going low signifies to the HX711 that the data is ready to be transmitted. The 24 bit 2's compliment data has a decimal range of -8388608 to 8388607.

The data in the above figure converts to – 65537, which is equivalent to -0.78 % in a range of -100 % to 100 %.

To compare the strain gauge against the designed values, a 1 Kg mass was placed at a known distance of 150 mm from the strain gauge to give a known torque.

$$\tau = F \times d \qquad \textbf{(6-2)}$$

Therefore:

$$\tau = 1kg \times 9.81 m/s^2 \times 0.15m$$
$$\tau = 1.47 N \cdot m$$

The calculated calibration factor from the design is 14,841 / N·m. This would result in a number of:

$$14{,}841 \times 1.47 = 21{,}816$$

A value of 742,050 was received rather than the calculated 21,816. This value was incorrect by a factor of about 34.

6.6.1.1 Investigating strain Error

Note that the accuracy of the strain gauge is unimportant for the success of the electronic ratchet, however an investigation took place to understand where the error may have come from. This investigation found a number of ways in which an error of such magnitude could have occurred.

- The study researched (B.M. Tymrak 2014) which revealed the Elastic Modulus of 3368 MPa was tested on material printed with a 100 % infill. The DSD was printed at 15% infill and therefore the value could be much lower. Two studies subsequently reviewed have measured the Elastic Modulus as low as 1000 MPa for a 10% infill (Antonio Lanzotti 2015) and (3D Matter 2015).
- The PLA has a clearance through the centre for the sensor cables to go through and therefore the effective thickness (t) and width will be less than measured. The measured thickness (t) value to the cable whole is 15 mm and the width (w) is 10 mm.

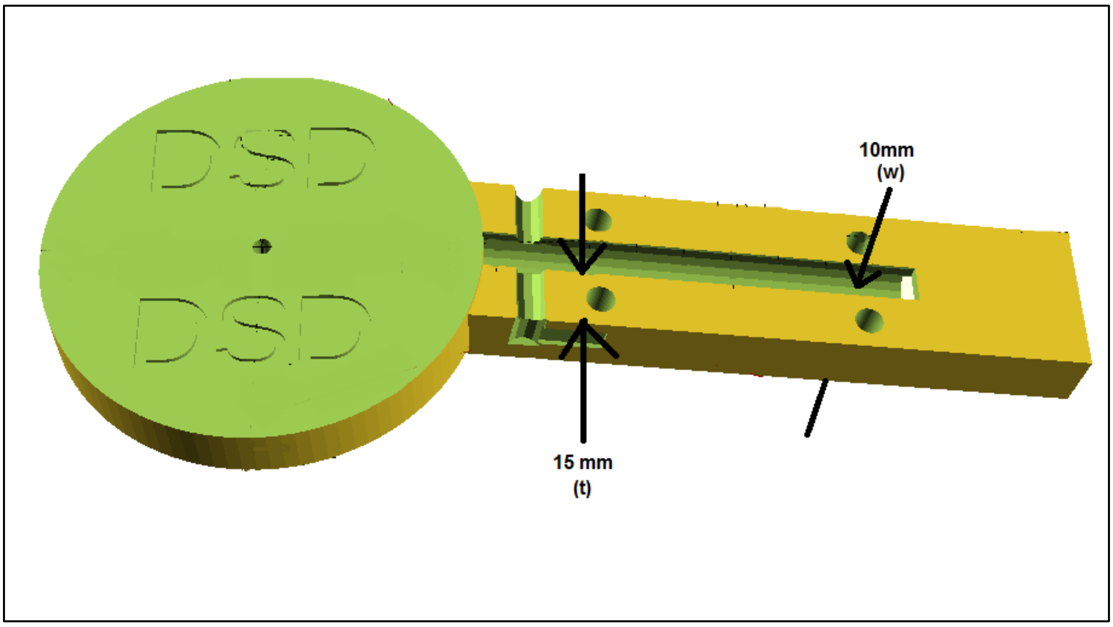


Figure 6-54: Thickness (t) from edge to cable hole

The strain equation can increase by a large amount if the new thickness, width and elastic modulus figures are used in equation (5-21)

$$\varepsilon = \frac{6(l-x)}{w \cdot t^2 \cdot E} F$$

Determining the factors that $w, t^2 and.E$ increase by:

	w	t	E
Original	15	0.035	3368
New	10	0.015	1000
Factor (1/(Original/New))	1.5	2.33	3.37
Total Factors ($w \cdot t^2 \cdot E$)	27.51		

These calculations have shown that if an error by a factor of 27 is feasible, then the measured error factor of 34 is also plausible.

6.6.1.2 Adjusting strain gauge calibration factor

To determine the new calibration figure, the old calibration figure is multiplied 50/1.47, which is 34.01.

$$Calibration.Value = 5307 \times 34.01$$
$$Calibration.Value = 520{,}646$$

This calibration factor was then used in the Arduino code in the ‘LC_Cal_Factor’ variable.

6.6.1.3 Testing the Electronic Ratchet

The Electronic ratchet control was tested by pressing the ‘Brake On’ button while the ‘Ratchet Mode’ check box was selected.

The ratchet worked, however a couple of issues were encountered.

- The speed threshold which turns the brake on when movement towards the face is attempted was set at 1 m/s which was too high. This allowed the arm to easily keep in a closed position rather than forcing the arm straight.
- The force required to keep the brake on when moving towards the face was slightly too high, allowing the brake to be released too early.

The speed threshold and the strain gauge value was reduced from 1 m/s to 0.2 m/s and from 0.15 N·m to 0.10 N·m respectively. Once completed, another test was completed.

The ratchet worked better than expected. Any attempt to move the arm towards the head would secure the brake, while only a slight force trying to open the arm was required to completely release the brake allowing the arm to freely extend.

The ratchet was tested with multiple attempts open then quickly attempt impact, as well as slower attempts, however the ratchet would stop the action every time prior to impact. The ratchet also gave a feeling that the arm was not restrained, as it could easily be moved in the open direction, and while in a mostly open state (greater the 90 ^{o} from closed position) the brake was completely free.

6.6.2 Speed Control Testing

The testing of speed control was completed by entering in a set-point and trying to attempt impact. When the set-point was raised, the speed that could be reached without braking increased. The output was quite bumpy initially due to an overactive controller. As soon as the speed set-point was exceeded the brake came on hard enough to slow the speed instantly, which allowed the brake to be released (as the speed was now below set-point).

When impact was attempted, the brake output would increase which reduces the speed of the elbow joint to below the set-point at times, which would cause the controller to reduce the output. This reduction in output allowed impact a few times during testing.

A modification was made to the speed controller, so that if 1 N·m of force was acting on the strain gauge during speed control braking, then braking would be increased to 100 % and will not release while the torque is greater than 1 N·m.

```
//  If while breaking the strain gauge measures an increase in
force which may cause impact, then apply brake fully
    if (StrainGauge > 1.0) {
      BrakeCntrl = 255;
    }
```

This worked very well. Attempted impact while in speed control was impeded. The following code addition was placed within the PID speed control code and can be seen in context in appendix D.

Chapter 7. – Conclusions

7.1 Overall Results

The project aim was to develop a splint device that electronically restricts the speed of rotation of the elbow joint to minimise harm in people who self-harm. This has been accomplished, with a device that can be used with people living with SIB.

The research has shown that there is nothing available to restrict movement and minimise harm when required, while giving freedom of movement when not required, for people living with severe autism or brain injuries who display self-injurious behaviour. The DSD will give an alternative to current methods which either totally restrain arm movement, involve aversive therapies such as shocking after impact is detected, or protect the head impact by using boxing head guards and boxing gloves.

Each of the program items within the original specification has been met, with many items being exceeded, including:

- 3D printing the device has allowed rapid prototyping to improve the design quickly, and will allow subsequent models to be easily reproduced. 3D printing also allows the components to be parameterised allowing modifications to be made to suit different people
- The Electronic Ratchet was not a part of the initial specification, however has become one of the key features of the device to allow a feeling of not being restrained, as well as improving the battery consumption of the DSD
- Developing an Android phone application has become integral to the success of the DSD. Being able to remotely control, monitor and calibrate the device has increased the safety, decreased the cost and has made interfacing to the device easy.

7.2 Learning Curve

The amount of learning required to complete the DSD was large. New skills learnt were;

- Arduino microcontroller integrated Development Environment (IDE)

- 3D Computer Aided Drafting Packages including OpenSCAD
- 3D printing software
- 3D printing
- MIT’s App Inventor Android phone development software

These skills took many hours to learn which are not evident when reviewing the device.

An important part of the engineering trade is to have the ability to quickly learn new skills and be able to apply those skills to develop existing and new technologies. The DSD is an example of learning multiple new technologies and integrating them to develop a device which is unique and performs a function which will return freedom and dignity to many.

7.3 The DSD

This project has successfully proven the concept that a device can restrict the arm movement dynamically only when required to prevent injury while maintaining movement and dignity when not required.

A Bluetooth Android application was developed to control the speed of the arm dynamically to a carer entered speed set-point, allow a carer to override the brake when required, allow calibration of sensors, and transmit data to the phone allowing monitoring of maximum impact force, maximum speed and current torque.

The electronic ratchet developed to solve the problem encountered when the arm was secured in a bent position allowing shoulder movement to continue impact has been a major success. This has allowed a sense of freedom when the arm is being stopped by always allowing movement in one direction (extending the arm), has saved battery life due to not braking constantly and has allowed the arm to be extended into a safe extended position without requiring heavy motors. With the torque being directly measureable for the ratchet, the strain gauge measurement also ensures that the brake is not released when there is force in the direction of the body.

To improve the feeling of freedom, the decision was also made to not brake for the last 15 ° from the fully open position while in ratchet mode. Once the arm goes past the 15 ° freedom position, the brake is again activated.

The DSD was designed and built utilising 3D printing technology, off the shelf microcontrollers, inexpensive sensors, an electromagnetic brake and a mobile phone application. The utilisation of these inexpensive open source technologies will allow health professionals and carers worldwide access to build, or have built, modify and improve the DSD inexpensively.

The DSD has the potential to revolutionise the care of people displaying Self Injurious Behaviour (SIB) by reducing the need for full mechanical restraint. It allows movement in a safe manner, restores civil liberties, restores dignity, and allows better therapy when compared to full restraint devices currently available on the market.

7.4 Further Research and Recommendations

The next stage of the DSD's development will be to:

- Customise the 3d coding so that the device can be customised to suit any arm measurements.
- Reduce the weight of the device to make it more user-friendly. Therefore using ERF fluids or make the electromagnetic component of the device with lighter materials.
- Trials also need to be completed to measure the success of the device for people with self-injurious behaviours.

7.5 Further Work

- Design and build a circuit board for both the brake driver and the main control board. This could then be sent out as part of a kit to people who want to build a DSD.
- Further work needs to be completed on the mechanical parts of the device, and then subsequent mechanical testing needs to be completed to ensure that the device will not break
- Have research completed by a local university on the effectiveness of the device on people living with SIB

- Approach an electromagnetic brake manufacturer to develop a brake designed specifically for the DSD, with weight saving a priority
- Develop the electronic box to enable external programming and battery charging

Further improvements to the code need to be considered during the next phase of the DSD. These include:

- When impact is detected, then brake for a fixed period of time rather than utilising a PID style control. A time period would be in the order of one to 2 seconds of braking.
- Implement low battery warning alerts for the main controller battery and the brake drive battery.
- Consider using a customised electronics board using the same ATMEGA328 processor that the Arduino uses to reduce the size of the electronics.

7.6 Other Potential Uses

The DSD may have many other uses other than that intended. The DSD may be used for:

- Rehabilitation or exercise purposes: The speed control can easily be changed to a torque control, which makes the user apply a torque to overcome the brake. This could then be used for strengthening of muscles, with different set-points for extension and flexion, and also the ability to modify torque depending upon position.
- The DSD may be modified for use on Prisoners to ensure they do not harm others.
- The Electronic Ratchet may have other applications which need to be explored.

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Appendix A – Project Specification

For: **M. Richardson**

Topic: AUTOMATIC SPLINT TO PREVENT SELF-HARM IN AUTISTIC AND BRAIN INURED PEOPLE.

Supervisor: A. Maxwell

Sponsorship: Own Project

Project Aim: To develop a splint device that electronically restricts the speed of rotation of the elbow joint to minimise harm in people who self-harm (reduce speed when the person is trying to strike themselves, and allow free movement at all other times).

Program:

1. Complete research on self-harm to gain insight to help develop the device.
2. Determine the amount of force/velocity required to cause harm, versus the speed required to use an arm normally for every-day tasks.
3. Research methods to detect acceleration and methods to slow down the acceleration to determine the most practical methods to detect and control the elbow joint speed.
4. Model the forces involved in the elbow joint of the arm, and develop a model to control the forces via a braking mechanism.
5. Develop electronics to amplify the velocity sensor so that the sensor can be used by a microprocessor circuit.
6. Either program a microprocessor system, or electronically create a control scheme to control the braking of the arm proportionally dependent upon speed via an adjustable setting, with the input being the velocity sensor, and the output being a braking mechanism.
7. Create a mechanical system to house the elbow joint and electronics.
8. Test and evaluate the device.
9. Submit an academic dissertation on the development of the device.

As time and resources permit:

1. Rather than a proportional style controller, create a controller that will allow the arm to travel maximum speed, and only breaking enough to reduce the speed to the speed set-point via a closed feedback loop.
2. Develop a remote control so that a carer can adjust the settings of the device from a distance.

Appendix B – Design Drawings

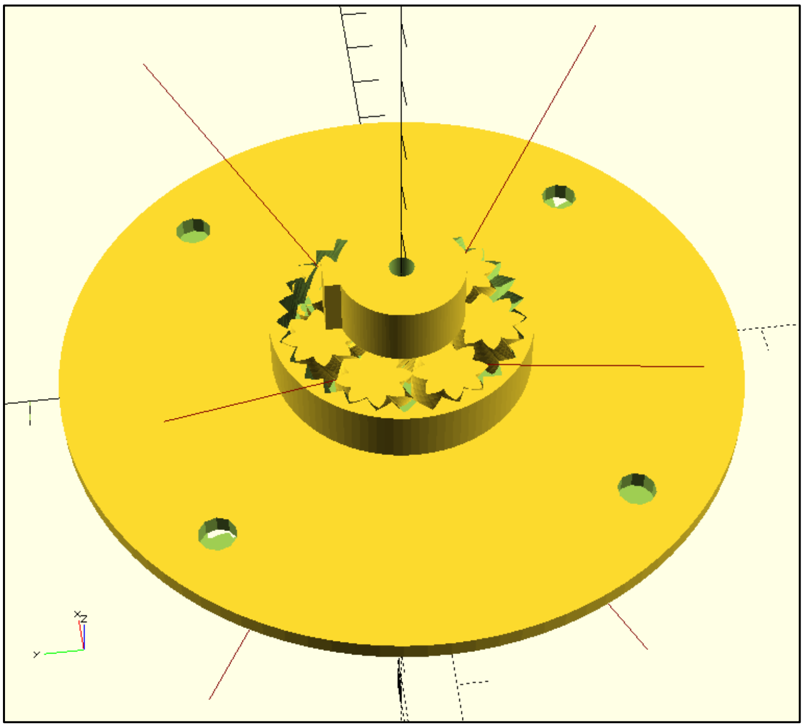


Figure B-1: Brake Bearing Top View

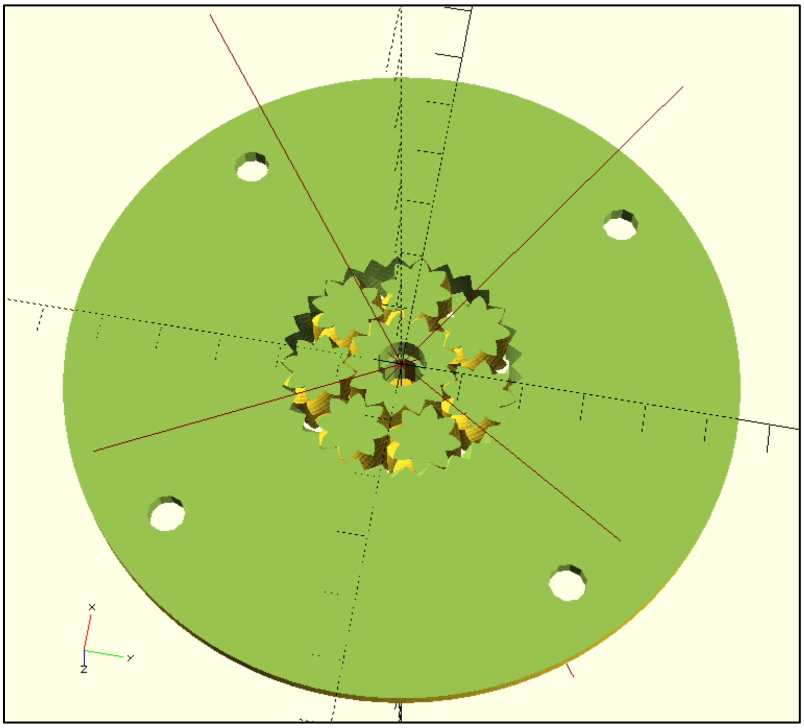


Figure B-2: Brake Bearing Bottom View

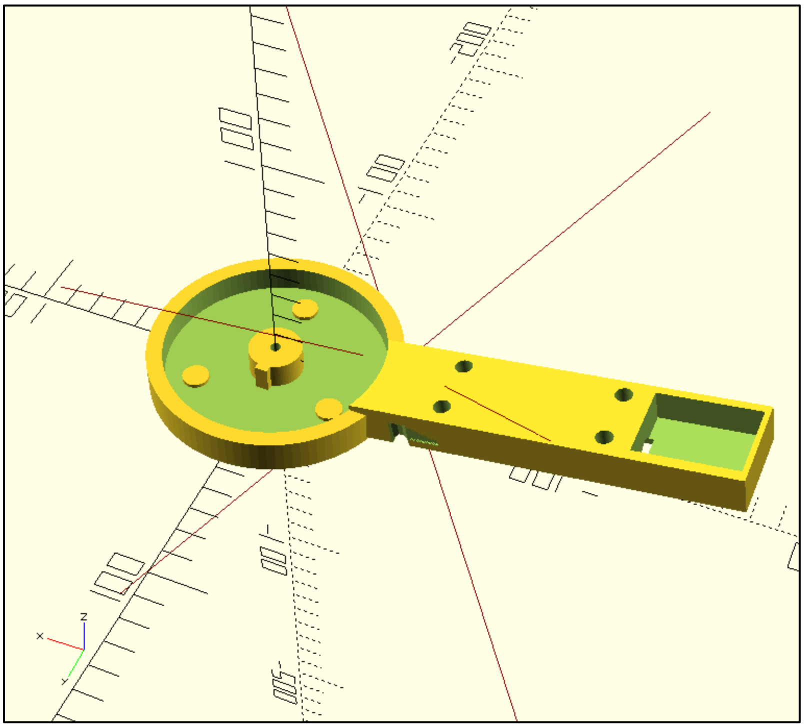


Figure B-3: Forearm Piece Bottom View

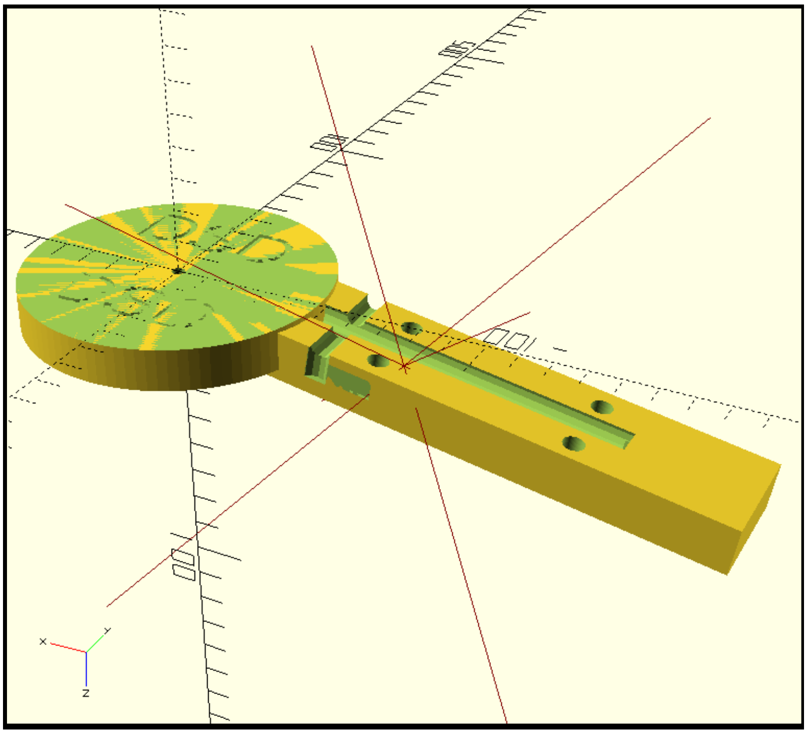


Figure B-4: Forearm Piece Top View

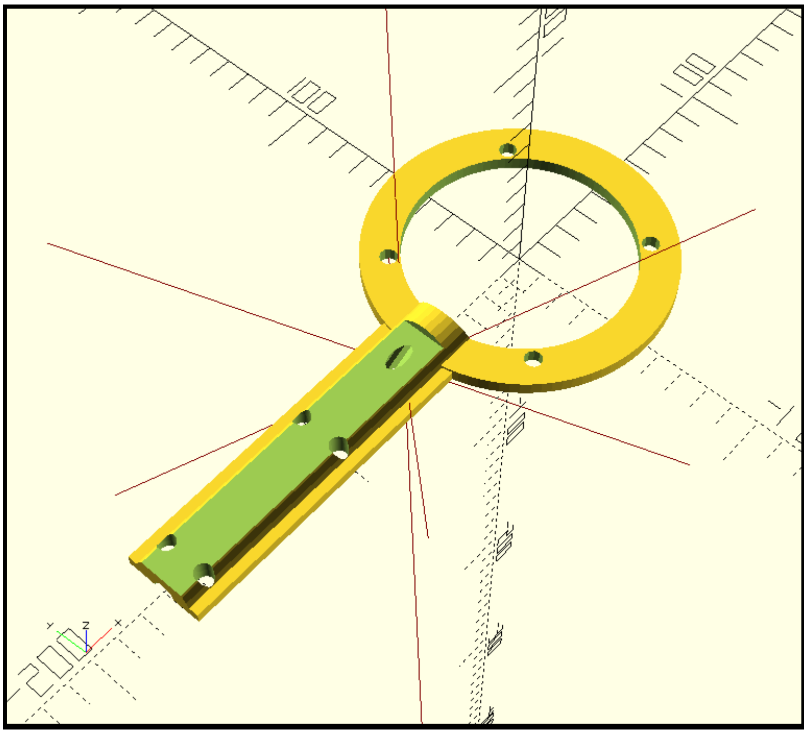


Figure B-5: Upper Arm Piece Top View

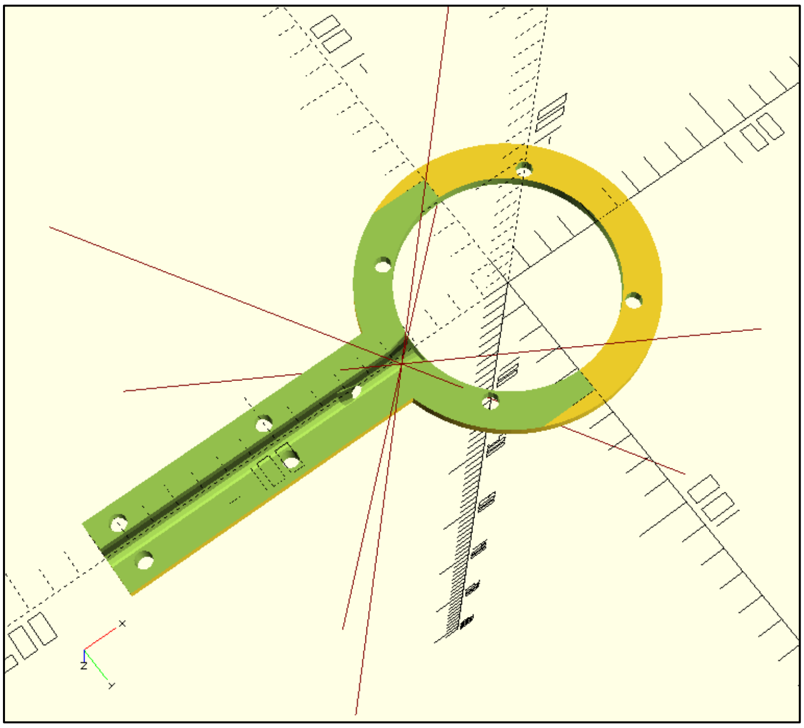


Figure B-6: Upper Arm Piece Bottom View

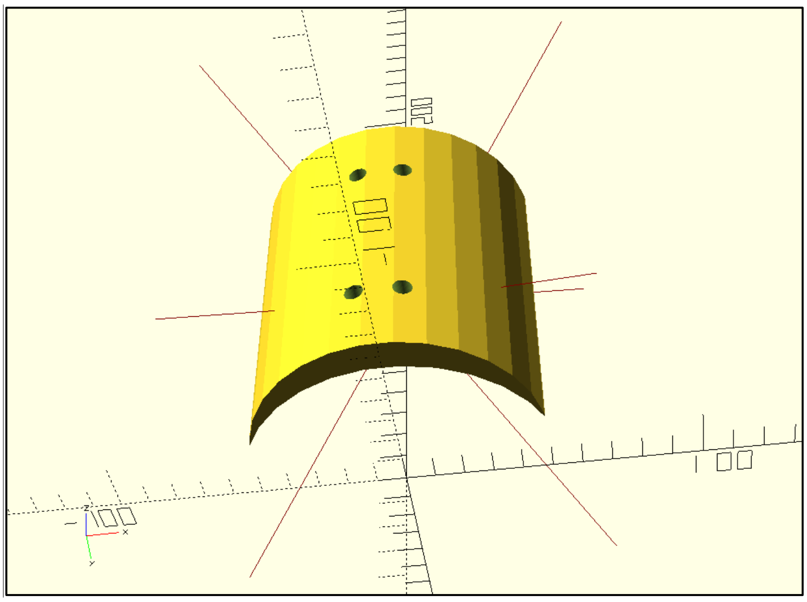


Figure B-7: Lower Arm Backing Plate

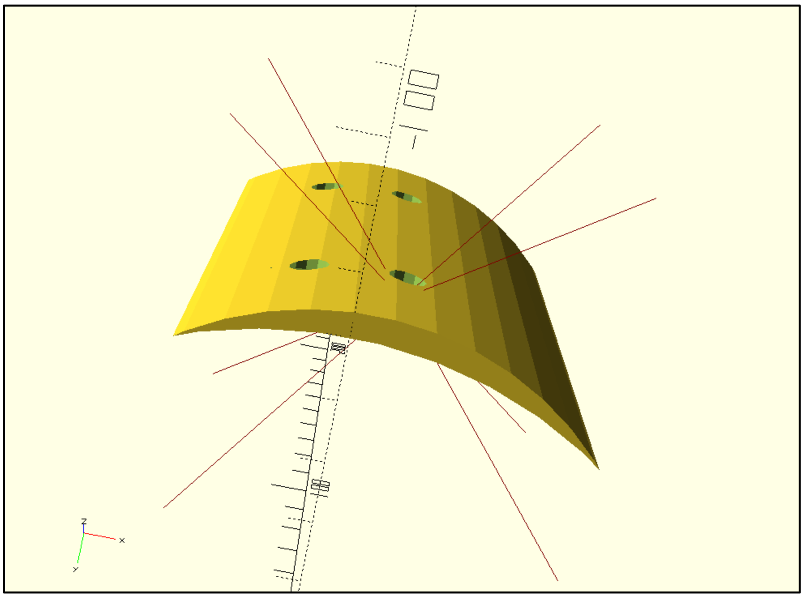


Figure B-8: Upper Arm Backing Plate

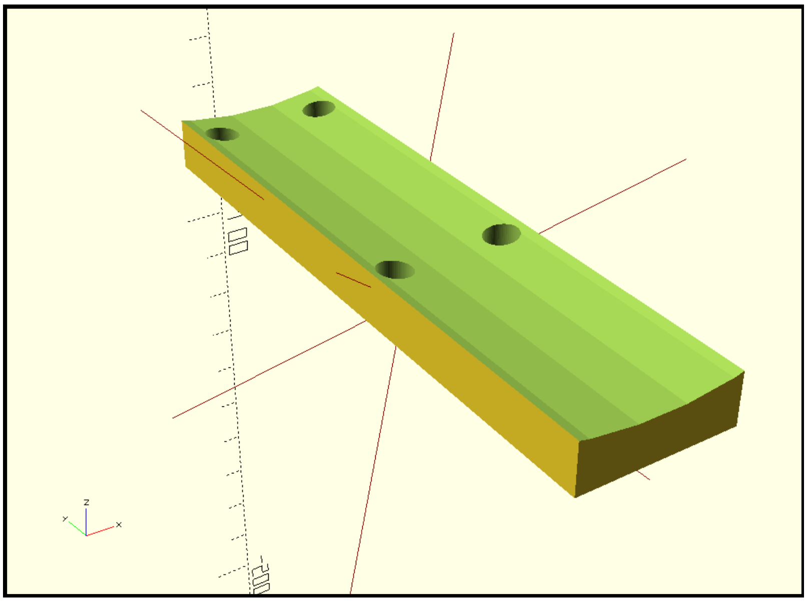


Figure B-9: Lower Arm Brace (for box)

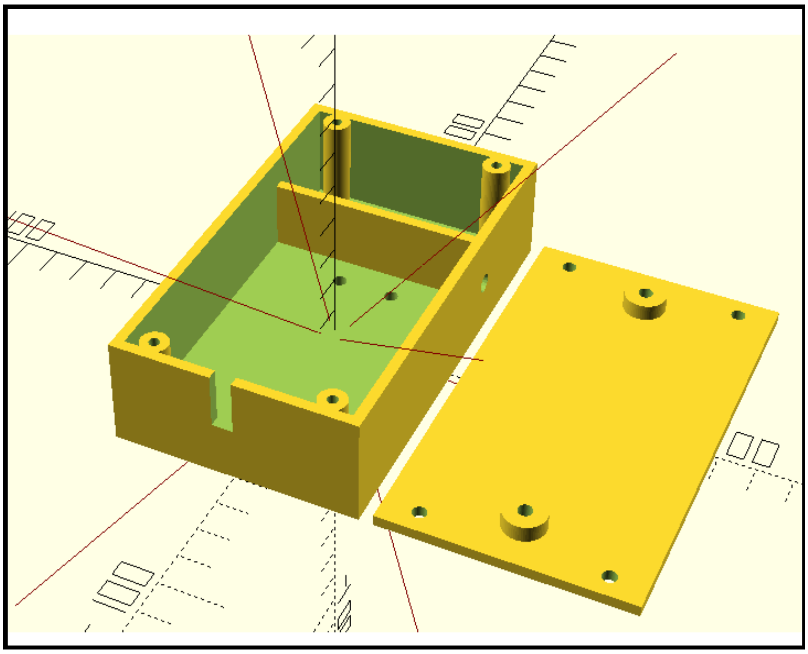


Figure B-10: Arduino Box

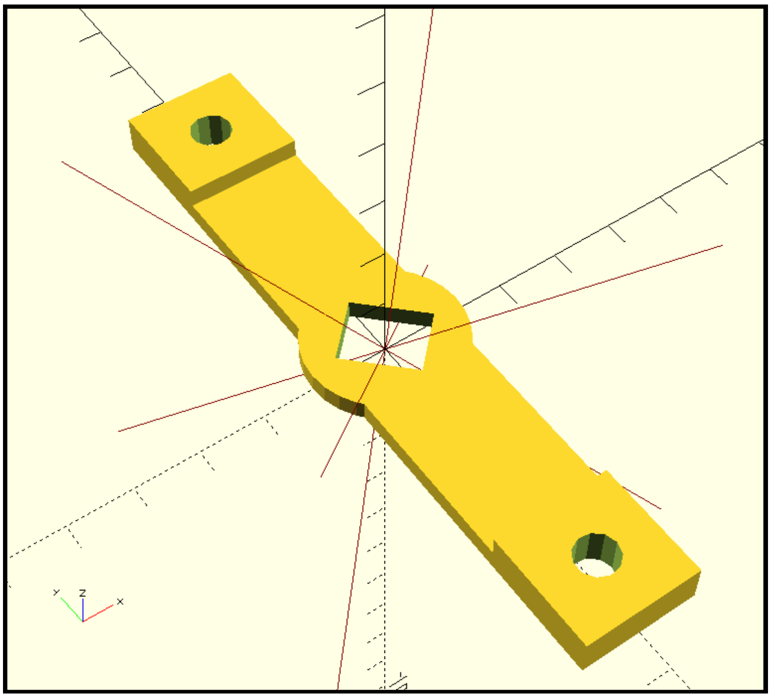
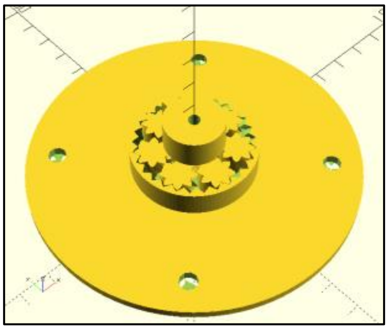


Figure B-11: Potentiometer Bracket

Appendix C – 3D Modelling Code

C.1: Brake Bearing Source Code



```
// Planetary gear bearing (customizable)

// Modified from Gear Bearing by Emmett found at
http://www.thingiverse.com/thing:53451. Sizing, flange, and keyed
shaft has been added, and more customising has been added to the
source code.

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the Creative Commons Attribution-NonCommercial-ShareAlike 4.0
International License. To view a copy of this license, visit
http://creativecommons.org/licenses/by-sa/4.0/ or send a letter to
Creative Commons, PO Box 1866, Mountain View, CA 94042, USA.


D                             =42;// outer diameter of ring
T                             =12;// thickness
tol                           =0.1;// clearance
number_of_planets             =7;
number_of_teeth_on_planets    =8;
approximate_number_of_teeth_on_sun  =13;
P                             =45;// pressure angle[30:60]
nTwist                        =1;// number of teeth to twist
across
w                             =20;// width of hexagonal hole
ad                            =34; // aditional radius of support
lip
st                            =3;// thickness of support lip
shaft                         = 21;// Length of internal shaft
extruding from inside
kw                            = 4.9;//Keyway Width
kd                            = 2.7;// Keyway depth
hr                            =45;//Securing hole radius
sc                            =3;//brim holes
DR                            =0.5*1;// maximum depth ratio of
teeth

//TO FIT POT!
Pot_D   = 15;
Pot_R   = 3.25;
Pot_Cl  = 4;
```
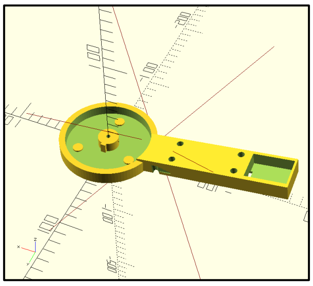

```
Cl_D    = 5;
Sl_W    = Pot_Cl + 1;
Sl_T    = 1;
Sl_D    = Cl_D;

m=round(number_of_planets);
np=round(number_of_teeth_on_planets);
ns1=approximate_number_of_teeth_on_sun;
k1=round(2/m*(ns1+np));
k= k1*m%2!=0 ? k1+1 : k1;
ns=k*m/2-np;
echo(ns);
nr=ns+2*np;
pitchD=0.94*D/(1+min(PI/(2*nr*tan(P)),PI*DR/nr));
pitch=pitchD*PI/nr;
echo(pitch);
helix_angle=atan(2*nTwist*pitch/T);
echo(helix_angle);
phi=$t*360/m;

difference(){
translate([0,0,T/2]){
    difference(){
        union(){
            cylinder(r=D/2,h=T,center=true,$fn=100);
            //Brim
            translate([0,0,-
(T/2)+(st/2)])cylinder(r=D/2+ad,h=st,center=true,$fn=100);

        }
        //Outer face gear
        herringbone(nr,pitch,P,DR,-tol,helix_angle,T+0.2);
    }
    rotate([0,0,(np+1)*180/ns+phi*(ns+np)*2/ns])
    difference(){
        mirror([0,1,0])
        //Inner Sun Gear
        herringbone(ns,pitch,P,DR,tol,helix_angle,T+3);
    }

for(i=[1:m])rotate([0,0,i*360/m+phi])translate([pitchD/2*(ns+np)/n
r,0,0])
        rotate([0,0,i*ns/m*360/np-phi*(ns+np)/np-phi])
            herringbone(np,pitch,P,DR,tol,helix_angle,T);
}
//Just to remove stuff sticking out the bottom, as herringbone is
symetrical
translate([-100,-100,-4])
cube([200,200,4]);
                  //holes
                 translate([hr*sin( 45),hr*sin
(45),0])cylinder(5,sc,sc)  ;
                 translate([hr*sin(-45),hr*sin
(45),0])cylinder(5,sc,sc)  ;
                 translate([hr*sin( 45),hr*sin(-
45),0])cylinder(5,sc,sc)  ;
                 translate([hr*sin(-45),hr*sin(-
45),0])cylinder(5,sc,sc)  ;

//To Fit Potentiometer
cylinder(h=Pot_D,r=Pot_R);
    cylinder(h=Cl_D,r=Pot_Cl,$fn=20);
    translate([0,-Pot_Cl,0]){
    cube([Sl_T,Pot_Cl*2,Pot_D]);}
}

//The centre shaft to fit inside
difference(){
    translate([0,0,T+1])cylinder(r=w/2,h=(shaft-1)/2,$fn=100);
    translate([0,0,T+2])cylinder(r=2,h=T+1,$fn=100);
}
//Keyway
translate([-kw/2,w/2-0.5,T+1]){
   cube([kw,kd,(shaft-1)/2]);
}

module rack(
    number_of_teeth=15,
    circular_pitch=10,
    pressure_angle=28,
    helix_angle=0,
    clearance=0,
    gear_thickness=5,
    flat=false){
addendum=circular_pitch/(4*tan(pressure_angle));

flat_extrude(h=gear_thickness,flat=flat)translate([0,-
clearance*cos(pressure_angle)/2])
    union(){
        translate([0,-0.5-
addendum])square([number_of_teeth*circular_pitch,1],center=true);
        for(i=[1:number_of_teeth])
            translate([circular_pitch*(i-number_of_teeth/2-
0.5),0])
            polygon(points=[[-circular_pitch/2,-
addendum],[circular_pitch/2,-addendum],[0,addendum]]);
    }
}

module herringbone(
    number_of_teeth=15,
    circular_pitch=10,
    pressure_angle=28,
    depth_ratio=1,
    clearance=0,
    helix_angle=0,
    gear_thickness=5){
union(){
    gear(number_of_teeth,
        circular_pitch,
        pressure_angle,
        depth_ratio,
        clearance,
        helix_angle,
        gear_thickness/2);
    mirror([0,0,1])
        gear(number_of_teeth,
            circular_pitch,
            pressure_angle,
            depth_ratio,
            clearance,
            helix_angle,
            gear_thickness/2);
}}
```

```
module gear (
    number_of_teeth=15,
    circular_pitch=10,
    pressure_angle=28,
    depth_ratio=1,
    clearance=0,
    helix_angle=0,
    gear_thickness=5,
    flat=false){
pitch_radius = number_of_teeth*circular_pitch/(2*PI);
twist=tan(helix_angle)*gear_thickness/pitch_radius*180/PI;

flat_extrude(h=gear_thickness,twist=twist,flat=flat)
    gear2D (
        number_of_teeth,
        circular_pitch,
        pressure_angle,
        depth_ratio,
        clearance);
}

module flat_extrude(h,twist,flat){
    if(flat==false)

linear_extrude(height=h,twist=twist,slices=twist/6)children(0);
    else
        children(0);
}

module gear2D (
    number_of_teeth,
    circular_pitch,
    pressure_angle,
    depth_ratio,
    clearance){
pitch_radius = number_of_teeth*circular_pitch/(2*PI);
base_radius = pitch_radius*cos(pressure_angle);
depth=circular_pitch/(2*tan(pressure_angle));
outer_radius = clearance<0 ? pitch_radius+depth/2-clearance :
pitch_radius+depth/2;
root_radius1 = pitch_radius-depth/2-clearance/2;
root_radius = (clearance<0 && root_radius1<base_radius) ?
base_radius : root_radius1;
backlash_angle = clearance/(pitch_radius*cos(pressure_angle)) *
180 / PI;
half_thick_angle = 90/number_of_teeth - backlash_angle/2;
pitch_point = involute (base_radius, involute_intersect_angle
(base_radius, pitch_radius));
pitch_angle = atan2 (pitch_point[1], pitch_point[0]);
min_radius = max (base_radius,root_radius);

intersection(){
    rotate(90/number_of_teeth)

circle($fn=number_of_teeth*3,r=pitch_radius+depth_ratio*circular_p
itch/2-clearance/2);
    union(){
        rotate(90/number_of_teeth)

circle($fn=number_of_teeth*2,r=max(root_radius,pitch_radius-
depth_ratio*circular_pitch/2-clearance/2));
```

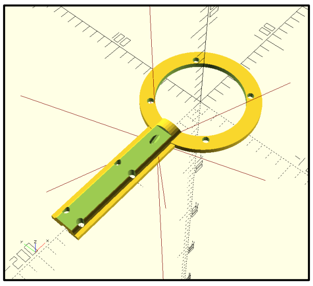
```
        for (i =
[1:number_of_teeth])rotate(i*360/number_of_teeth){
            halftooth (
                pitch_angle,
                base_radius,
                min_radius,
                outer_radius,
                half_thick_angle);
            mirror([0,1])halftooth (
                pitch_angle,
                base_radius,
                min_radius,
                outer_radius,
                half_thick_angle);
        }
    }
}}
module halftooth (
    pitch_angle,
    base_radius,
    min_radius,
    outer_radius,
    half_thick_angle){
index=[0,1,2,3,4,5];
start_angle = max(involute_intersect_angle (base_radius,
min_radius)-5,0);
stop_angle = involute_intersect_angle (base_radius, outer_radius);
angle=index*(stop_angle-start_angle)/index[len(index)-1];
p=[[0,0],
    involute(base_radius,angle[0]+start_angle),
    involute(base_radius,angle[1]+start_angle),
    involute(base_radius,angle[2]+start_angle),
    involute(base_radius,angle[3]+start_angle),
    involute(base_radius,angle[4]+start_angle),
    involute(base_radius,angle[5]+start_angle)];

difference(){
    rotate(-pitch_angle-half_thick_angle)polygon(points=p);
    square(2*outer_radius);
}}
// Mathematical Functions
//===============
// Finds the angle of the involute about the base radius at the
given distance (radius) from it's center.
function involute_intersect_angle (base_radius, radius) = sqrt
(pow (radius/base_radius, 2) - 1) * 180 / PI;
// Calculate the involute position for a given base radius and
involute angle.
function involute (base_radius, involute_angle) =
[
    base_radius*(cos (involute_angle) + involute_angle*PI/180*sin
(involute_angle)),
    base_radius*(sin (involute_angle) - involute_angle*PI/180*cos
(involute_angle))
];
```

C.2: Forearm Piece



```
// Forearm Piece for DSD

R = 82.5;   // Recess for top of brake Diameter
T = 3;      // Material Thickness
w = 3;      // Width of Centre Hole
d= 10;      // Depth of recess
sl = 180;   //Splint Support Length
st = 15;    //Splint Support Thickness
sw = 35;    //Splint Support Width
Ph = 1.5;   //Peg Height
Pw = 5;     //Peg Width
Pr = 30;    //Peg Radius from Centre
Pa = 25.4;  // Peg Angle from bottom
sc=3;       //Centre Securing Hole Radius
Sr=10;      //Shaft Radius
Sl=21;      //Shaft Length
kw = 4.9;   //Keyway Width
kd = 2.7;   // Keyway depth
HL = 29.8;  //Hole Centre Length
HW = 10.4;  //Hole Centre Width


difference(){

union()
{
//The centre shaft to fit inside
translate([0,0,T])cylinder(r=Sr,h=(Sl-1)/2,$fn=100);

//Keyway
translate([-kw/2,Sr-0.5,T])
   cube([kw,kd,(Sl-1)/2]);

//3 Pegs;
translate([Pr*sin(Pa-90),Pr*sin(Pa),T])cylinder(r=Pw,h=Ph) ;
translate([Pr*sin(Pa-90+120),Pr*sin(Pa+120),T])cylinder(r=Pw,h=Ph)
;
translate([Pr*sin(Pa-90+240),Pr*sin(Pa+240),T])cylinder(r=Pw,h=Ph)
;

//
difference()
    {
    union()
        {
    //Main Cylinder Outside
    cylinder(r=R/2+2*T,h=d+T,$fn=100);

            //Strengthener main beam
   translate([-w,-sw/2,-2*T]){rotate([10,0,90]){

       difference(){

  cube([sw,sl,st]);

  //Strain Gauge Insert
    translate([-2,55,0])cylinder(h=10,r=4);
    translate([sw+2,55,0])cylinder(h=10,r=4);
    translate([0,58,3])cube([1,14,6]);
    translate([sw-1,58,3])cube([1,12,6]);

    //Delete Holes
    for(p = [[HW,HL],[-HW,HL],[HW,-HL],[-HW,-HL]])
      translate([p[0]+17,p[1]+100,6])
cylinder(20,sc,sc,center=true,$fn=60);

        //Cable holes
    translate([sw,55,0])rotate([-90,0,90])cylinder(h=sw,r=3);
translate([sw/2,40,1])rotate([-90,0,0])cylinder(h=102,r=4.5);
        //Accelerometer Gap
       translate([3,140,3])cube([28,38,20]);
   }}}
   //end difference
        }

//Cylinder Centre Cleanout
    translate([0,0,T])
    cylinder(r=R/2,h=d+20,$fn=100);

        }

}
//Centre Securing Hole
 translate([0,0,-3])cylinder(r=2,h=T+20,$fn=100);
//Flat Bottom for Printing
rotate([90,0,0])translate([-120,-20,-50])cube([200,20,100]);

//DSD Embossing
linear_extrude(1){rotate([0,180,0]){translate([-
27,15,0])text("DSD",18);
translate([-27,-30,0])text("DSD",18);
}
}

}
```

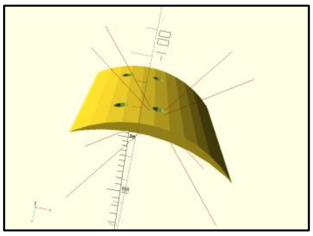
C.3: Upper Arm Piece



```
// Upper Arm Piece for DSD


R   = 110;  // Recess for top of brake Diameter
d   =12;    // Depth of recess
sl  = 170;  //Splint Length
st  = 4;    //Splint Thickness;
sw  = 30;   //Splint Width
ir  =41;    // Inside Hole Radius
hr  =45;    //Hole Radius
sc  =3.2;   //Securing Hole Radius
HW  =8;     //Hole Width
HL  =30;    //Hole Length

union(){
difference(){
            union()
                {
    cylinder(r=R/2,h=5,$fn=100);

                    //Main Shaft
    rotate([0,270,0])cylinder(h=sl,r=12);
          translate([0,-15,0])rotate([0,0,90]) cube([sw,sl,st]);

                }
              //Remove Centre radius
           cylinder(r=ir,h=d,$fn=100);
            //Flatten Bottom
                rotate([90,0,0])translate([-200,-20,-
50])cube([200,20,100]);
            //Flatten top
             translate([-130,0,11])cube([160,20,5],true);
                  //holes

translate([hr*sin(45),hr*sin(45),0])cylinder(5,sc,sc)   ;
                 translate([hr*sin(-
45),hr*sin(45),0])cylinder(18,sc,sc)   ;
                 translate([hr*sin(45),hr*sin(-
45),0])cylinder(5,sc,sc)   ;
                 translate([hr*sin(-45),hr*sin(-
45),0])cylinder(6,sc,sc)   ;
              // Cable Tunnel
    translate([-ir,0,0])rotate([0,270,0]){cylinder(21,6,1)   ;
    cylinder(h=sl,r=4);}
    translate([-ir-10,0,15])rotate([0,240,0])cylinder(25,3,3);

// splint connection holes

    for(p = [[HL,HW],[-HL,HW],[HL,-HW],[-HL,-HW]])
```

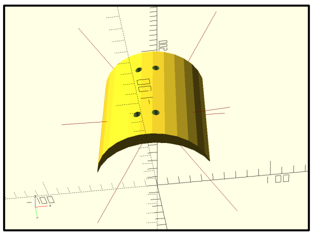
```
        translate([p[0]-130,p[1],0])
cylinder(20,sc,sc,center=true,$fn=60);

    }
}
```

C.4: Lower Arm Backing Plate



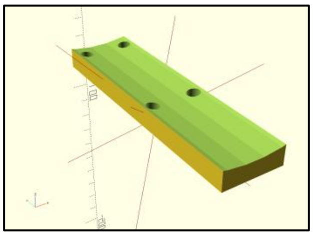
```
// Lower Arm Backing Plate for DSD

rad = 50;
length=110;
sc=3.2;
st=4;
offset=24;
nut_rec=5;

difference(){
    translate([3,-offset,0])cylinder(length, rad,rad,$fn=50);
    cylinder(h=length,r=rad*1.4,$fn=50 );
    translate([-rad,0,0])
    cube([rad*2,rad*2,length]);


    translate([-8,-
rad*1.4+4,25])rotate([90,0,0])cylinder(h=nut_rec,r=6,$fn=6);
    translate([-8,-
rad*1.4,25])rotate([90,0,0])cylinder(h=20,r=sc);
    translate([8,-
rad*1.4+4,25])rotate([90,0,0])cylinder(h=nut_rec,r=6,$fn=6);
    translate([8,-rad*1.4,85])rotate([90,0,0])cylinder(h=20,r=sc);
    translate([-8,-
rad*1.4+4,85])rotate([90,0,0])cylinder(h=nut_rec,r=6,$fn=6);
    translate([-8,-
rad*1.4,85])rotate([90,0,0])cylinder(h=20,r=sc);
    translate([8,-
rad*1.4+4,85])rotate([90,0,0])cylinder(h=nut_rec,r=6,$fn=6);
    translate([8,-rad*1.4,25])rotate([90,0,0])cylinder(h=20,r=sc);
}
```

C.5: Upper Arm Backing Plate



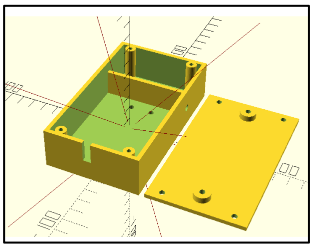
```
//Upper Arm Insert for DSD

rad = 50;
length=110;
sc=3.2;
st=4;
offset=16;
nut_rec=7;

difference(){
    translate([0,-offset,0])cylinder(h=length, r=rad);
    cylinder(h=length,r=rad*1.1 );
    translate([-rad,0,0])
    cube([rad*2,rad*2,length]);


     #translate([-8,-rad-2,25])rotate([90,0,0])cylinder(h=nut_rec,r=6,$fn=6);

    translate([-8,-rad-2,25])rotate([90,0,0])cylinder(h=20,r=sc);
    #translate([8,-rad-2,25])rotate([90,0,0])cylinder(h=nut_rec,r=6,$fn=6);
    translate([8,-rad-2,85])rotate([90,0,0])cylinder(h=20,r=sc);
    #translate([-8,-rad-2,85])rotate([90,0,0])cylinder(h=nut_rec,r=6,$fn=6);
    translate([-8,-rad-2,85])rotate([90,0,0])cylinder(h=20,r=sc);
    #translate([8,-rad-2,85])rotate([90,0,0])cylinder(h=nut_rec,r=6,$fn=6);
    translate([8,-rad-2,25])rotate([90,0,0])cylinder(h=20,r=sc);
}
```

C.6: Lower Arm Brace



```
// Lower Arm Brace for DSD

rad = 50;
length=120;
sc=3.2;
st=4;
offset=24;
nut_rec=5;

rotate([90,0,0]){
difference(){
    translate([-15,-78,17])
    cube([30,10,length]);
    cylinder(h=length+18,r=rad*1.4,$fn=50 );
    translate([-10.5,-
rad*1.3,25])rotate([90,0,0])cylinder(h=40,r=sc);
    translate([10.5,-
rad*1.3,85])rotate([90,0,0])cylinder(h=40,r=sc);
    translate([-10.5,-
rad*1.3,85])rotate([90,0,0])cylinder(h=40,r=sc);
    translate([10.5,-
rad*1.3,25])rotate([90,0,0])cylinder(h=40,r=sc);

}}
```

C.7: Arduino Box

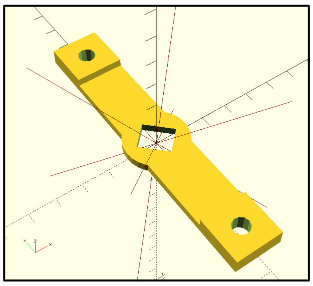


```
//Arduino Box for DSD device


encl();

r = 1.5; // Hole radius
// box parameters
t = 3;              // Box wall thickness
```

```
h = 30;            // Box Height
BL  =   120;        // Box Length
BW  =   70;         // Box Width
HL  =   54;         // Hole Length (From centre)
HW  =   25;         // Hole Width(from centre)
BHL  =   30;         // Bottom Hole Length (From centre)
BHW  =   8;         // Bottom Hole Width(from centre)

module encl()
{
   rotate([180,0,0]) translate([0,BW+4,-t/2]) lid();
   rotate([  0,0,0]) translate([0,0,h/2]) box();

}


module lid()
{
   union()
   {
      difference()
      {
          union(){
         translate([0,0,0]) cube([BL,BW,t],center=true);

              for(p = [[46.5,0],[-46.5,0]])
            translate([p[0],p[1],-2.5])
cylinder(t+4,6,6,center=true,$fn=60);
          }


         for(p = [[HL,HW],[-HL,HW],[HL,-HW],[-HL,-HW],[46.5,0],[-
46.5,0]])
            translate([p[0],p[1],0])
cylinder(20,2,2,center=true,$fn=60);
      }

   }
}
//---------------------------------------------------------|
module box()
{
   difference()
   {
      union()
      {
         difference()
         {
            translate([0,0,0]) cube([BL,BW,h],center=true);
            translate([0,0,t]) cube([BL-t*2,BW-
t*2,h],center=true);
         }

         for(p = [[HL,HW],[-HL,HW],[HL,-HW],[-HL,-HW]])
            translate([p[0],p[1],0])
cylinder(h,4,4,center=true,$fn=60);

         translate([30,0,-4]) cube ([t,BW,h-8],center=true);
//Divider
      }

      translate([-BL/2,0,0]) cube ([t,6,h]); //Solt for cables
```

```
     translate([22,0,0])rotate ([90,0,0]) cylinder
(50,2.5,2.5,$fn=20);
      //Switch Hole

      for(p = [[HL,HW],[-HL,HW],[HL,-HW],[-HL,-HW]])
         translate([p[0],p[1],0])
cylinder(h+0.2,1.5,1.5,center=true,$fn=50);

          for(p = [[BHL,BHW],[-BHL,BHW],[BHL,-BHW],[-BHL,-BHW]])
        translate([p[0]-10,p[1],-13])
cylinder(5,2,2,center=true,$fn=60);
   }
}
```

C.8: Potentiometer Bracket



```
//Securing hole radius
hr=45;
//brim holes
sc=3.2;
//Bracket Width
pw=10; //Pot Width
pl=15; //Pot Length
bw=pw+8; //Bracket Width
bt=3;//Bracket Thickness

translate([0,0,bt/2]){
difference(){
union(){cube([bw,hr*2.2,bt],true);
    cylinder(bt,bw/1.5,bw/1.5, true);
 translate([0, hr,bt/2]) cube([bw,bw,6],true);
 translate([0,-hr,bt/2]) cube([bw,bw,6],true);
}
 rotate([0,0,45])cube([10,12,bt],true);
 translate([0,hr,0])cylinder(10,sc,sc,true)   ;
 translate([0,-hr,0])cylinder(10,sc,sc,true);
    }
}
```

Appendix D - Arduino Code

Main Code

```
/*
 * 2015 Arduino code for the Dynamic Splint Device (DSD). This is
a USQ final year project
 * Written by Mark Richardson, University of Southern Queensland
(USQ) Student Number 003124006
 *
 * // Copyright 2014, Mark Richardson. This work is licensed under
the Creative Commons Attribution-NonCommercial-ShareAlike 4.0
International License. To view
 * a copy of this license, visit
http://creativecommons.org/licenses/by-sa/4.0/ send a letter to
Creative Commons, PO Box 1866, Mountain View, CA 94042, USA.
 *
 *
 */


#include <Hx711.h>                //  Hx711 file sourced at GITHUB
(Bodge, 2014)
#include <AcceleroMMA7361.h>      // Accelerometer Include File
sourced at GITHUB (jeroendoggen, 2012)



//*********************Declarations*******************
#define DT 5      // Data pin for Load cell amplifier (Hx711)
serial data.
#define SCK 6     // Clock data pin for Load cell amplifier serial
data timing
#define LC_Cal_Factor -520646 //Calculated 15307 gives 1 Nm
(Theoretical value)

HX711 scale(DT, SCK);//Serial data and clock pulses terminals 5
and 6.
AcceleroMMA7361 ThreeAxisA;

boolean Auto          = false;  //Auto Speed Control
boolean RS            = false;  //Reset Speed Sensor
boolean RF            = false;  //Reset Force Sensor
boolean BrakeOn       = false;  //Digital from phone to apply
Brake
boolean Manual        = false;
boolean Ratchet       = true;   //Digital from phone to put
Ratchet ON

char recd_dat;                  // variable for receiving data
from blue-tooth serial port

int AxRaw;
int AyRaw;
int AzRaw;
int BrakeCntrl        = 0;      // Brake control bit
int BrakePwm          = 11;     //analogue output PIN for brake
(11)
int DigitValue        = 0;      //Stored Analogue Value from Phone

int ManSP           = 0;

int on_brd_led        = 13;     // On-board LED pin detail

int SpeedSens         = 4;      //Speed Sensor Pin 4
int SpeedSP           = 0;

long previousMillis3  = 0;      //Used for getting strain data
every 100ms
long currentMillis3;            //"                            "
long previousMillis2  = 0;      //Used for printing data to phone
app
long currentMillis2;            //"                            "
long currentPotMilli  = 0;      // For elbow speed calculation
long previousPotMilli = 0;      //"                            "
long Pot              = 0;
long TimingMilli1     = 0;
long TimingMilli2     = 0;

float Ax;
float Ay;
float Az;
float FilterAcc       = 1;      //Accelerometer filter coefficient
float FilterSp        = 0.3;    // Speed Filter Coefficcient
float Force           = 0;
float D_Val           = 1;      //Derivative value for speed
control
float DerivativeOut   = 0;      //Output from Derivative Control
float Error           = 0;      //Speed Control Error
float GainOut         = 0;      //Output from Proportional control
float I_Val           = 0.1;    // Integral for Speed Control
float IntegralOut     = 0;      //Output from Integral Control
float MaxSpeed        = 0;
float MaxForce        = 0;
float NewAccel        = 0;
float P_Val           = 1;      // Gain for speed control
float PIDOut          = 0;      // Addition of P, I and D actions
float Position        = 0;      //Position in degrees from
straight arm
float PositionOld     = 0;
float Pos_Offset      = -45;    //The offset for position to make
contracted position = -45 (dependent upon potentiometer (one time
setup!))
float Radius          = 300.00; //This is the mm between elbow
pivot and middle of fist
float Speed           = 0;
float SpeedRaw        = 0;
float StrainGauge     = 0;      //Raw Value from Strain Gauge
float TotalAccel      = 0;
float TotalSpeed      = 0;
float XSpeed          = 0;
float YSpeed          = 0;
float ZSpeed          = 0;

//************************ INITIAL SETUP *************************
void setup() {

  // Setup the Serial Communications:
```

```
  // Used to receive the data from Blue-tooth module
  // and to send to serial monitor when debugging
  Serial.begin(9600);

  //***** Brake Control Frequency Setup *******
  TCCR2B = TCCR2B & B11111000 | B00000001;     // Timer two divide
by set to   1 for 31.3 KHz

  scale.set_scale(LC_Cal_Factor); //Adjust to this calibration
factor
  scale.tare(); // Tare the load cell to zero

  //NOTE: Sleep/self-test/zeroGPin not used. Pin 2 is a spare pin
chosen.
  ThreeAxisA.begin(2, 2, 2, 2, A1, A2, A3); //(Sleep pin,
SelfTestPin, ZeroGPin, GravitySelect, X, Y, Z)
  ThreeAxisA.setARefVoltage(3.3); //The Analogue reference voltage
for the accelerometer is 3.3V
  ThreeAxisA.setSensitivity(LOW); //HIGH = +-1.5g, LOW = +-6g
  ThreeAxisA.setAveraging(10); //average of 10 samples ()
  ThreeAxisA.setOffSets(-12 * 8, 10 * 8, 43 * 8); //Set
experimentally as a start figure.

  // Digital Pin Mode Setup
  pinMode(on_brd_led, OUTPUT);
  digitalWrite(on_brd_led, LOW);
  pinMode(BrakePwm, OUTPUT);
}

void loop() {
  //Call the main menu.
  mainMenu();
}

//*********************** MAIN PROGRAM *********************
void mainMenu() {
  TimingMilli1 = millis();
  //*****   READING BLUETOOTH   ******


  if ( Serial.available() ) // if serial data is available to read
  {
    recd_dat = Serial.read(); //read data & store it in Ҳecd_datь



    //*****ANALOGUES FROM PHONE *********

    /* Analogues from phone are sent with a leading 1 for speed, a
leading 2 for manual output.
       Therefore this code determines which, and decodes the
values;
       Values are decoded by multiplying each subsequent digit by
10 to account for the order of digits.
       i.e: first digit received, then first digit multiplied by
10, and second digit added, then total
       divided by 10 and next digit added etc until the end of
number character (/) is received.
    */

    if ( isdigit(recd_dat)) // || recd_dat == ',' ) // if serial
data is available to read, and it is a digit
```

```
    {
      DigitValue = (DigitValue * 10) + (recd_dat - '0'); //'-0'
turns ASCII into numeral 1-9
    }
    else if (recd_dat == '/') //ALL sets of analogues ens in "/"
    {
      if (DigitValue >= 0 && DigitValue < 200 || DigitValue ==
1100) { //If a 1 is seen as a leading digit, then Speed SP
        if (DigitValue == 1100) {
          SpeedSP = DigitValue - 1000;
        }
                else {
          SpeedSP = DigitValue - 100;
        }
        DigitValue = 0;
      }
      else if (DigitValue >= 200 && DigitValue < 300 || DigitValue
== 2100) { //If a 2 is seen as a leading digit then Force SP
        if (DigitValue == 2100) {
          ManSP = DigitValue - 2000;
        }
        else  {
          ManSP = DigitValue - 200;
        }
        DigitValue = 0;
      }

    }

  }
  //*******   DIGITALS FROM PHONE   ********
  if (recd_dat == 'B' ) { // if 'B' was received
    //JY-MCU Blue-tooth to UART Wireless Serial Port Module (SKU:
010-JYMCUBLUETOOTH)
    //7
    digitalWrite(on_brd_led, HIGH); // turn ON LED (THIS WILL BE
BRAKE)
    BrakeOn = HIGH;
    recd_dat = 0;
  }
  else if (recd_dat == 'b') {
    digitalWrite(on_brd_led, LOW); // otherwise switch OFF
(Dynamic?)
    BrakeOn = LOW;
    recd_dat = 0;
    Serial.println("BRAKE OFF!!!");
  }
  else if (recd_dat == 'R') {
    Ratchet = HIGH;
    recd_dat = 0;
  }  else if (recd_dat == 'r') {
    Ratchet = LOW;
    recd_dat = 0;
  }
  else if (recd_dat == 'M') { //Manual means that the force is
applied dependant upon the manual set-point
    Manual = HIGH;
    Auto = LOW;
    ManSP = 0;
    recd_dat = 0;
  }
  else if (recd_dat == 'm') {
    Manual = LOW;
    ManSP = 0;
    recd_dat = 0;
  }
  else if (recd_dat == 'C') { //Automatic Speed Control
    Auto = HIGH;
    Manual = LOW;
    recd_dat = 0;
  }
  else if (recd_dat == 'c') {
    Auto = LOW;
    recd_dat = 0;
  }



  if (recd_dat == 'A') {          //*CALIBRATE ACCELEROMETER*
    ThreeAxisA.calibrate();
    recd_dat = 0;
  }
  else if (recd_dat == 'L') {  //*****CALIBRATE LOAD CELL
    scale.tare();
    recd_dat = 0;
  }
  else if (recd_dat == 'S' && RS == false) {
    RS = HIGH;
    recd_dat = 0;
  }
  else if (recd_dat == 'F') {
    RF = HIGH;
    recd_dat = 0;
  }


  //******** Elbow Speed calculation *********




  //The following is the speed from the potentiometer
  Pot = (analogRead(SpeedSens)); //Input A4 0-1024 = 360 degrees
  Position = (float(Pot) * 360 / 1023) + Pos_Offset;
  currentPotMilli = millis();

  if (currentPotMilli - previousPotMilli > 5) {

    SpeedRaw = -( (( (Position - PositionOld) / 360) * 2.00 * PI *
Radius) / max(1, (currentPotMilli - previousPotMilli))); //mm/ms,
or m/s
    Speed = Speed * (1.00 - FilterSp) + SpeedRaw * FilterSp;
    PositionOld = Position; //for maximum delay, this is
calculated prior to collecting new pot value
    previousPotMilli = currentPotMilli;
  }
  //********* Maximum Speed Reading *********

  MaxSpeed = max(Speed, MaxSpeed);
  if (RS == true) {
    MaxSpeed = 0;
  }
  //******* Accelerometer Force Calculation **********

  AxRaw = ThreeAxisA.getXAccel();
  AyRaw = ThreeAxisA.getYAccel();
  AzRaw = ThreeAxisA.getZAccel();

  Ax = Ax * (1.00 - FilterAcc) + AxRaw * FilterAcc;
  Ay = Ay * (1.00 - FilterAcc) + AyRaw * FilterAcc;
  Az = Az * (1.00 - FilterAcc) + AzRaw * FilterAcc;
  TotalAccel = sqrt(sq(float(Ax)) + sq(float(Ay)) +
sq(float(Az)));

  Force = TotalAccel / 100.0; // Force in g's


  //******** Strain Gauge sensor collection **********
  //USE TIMER TO ONLY SEND SERIAL EVERY
100ms!!!!!!!!!!!!!!!!!!!!!!!!!!!
  currentMillis3 = millis();
  if (currentMillis3 - previousMillis3 > 100) {
    previousMillis3 = currentMillis3;
    StrainGauge = scale.get_units();
  }

  //********* Maximum Force Reading *********

  MaxForce = max(Force, MaxForce);
  if (RF == true) {
    MaxForce = 0;
  }

  RS = LOW;//""                 ""
  RF = LOW;//Resetting the reset bits to low

  //********Send Analogues To Phone  *********
  char  buffer[15] = "";


  //USE TIMER TO ONLY SEND SERIAL EVERY TWO SECONDS!
  currentMillis2 = millis();
  if (currentMillis2 - previousMillis2 > 2000) {
    previousMillis2 = currentMillis2;


    Serial.print("An,");//To print to Android App, it accepts 3
comma separated values following "An"
    Serial.print(MaxSpeed, 1); Serial.print(",");
Serial.print(MaxForce, 2); Serial.print(",");
Serial.println(StrainGauge);

    //!!!!!!!!!!!!!!!!!!!!!!!!!!!!Uncomment for
debugging!!!!!!!!!!!!!!!!!!!!
    //Serial.print(" strain:");Serial.print(StrainGauge,1);
    //Serial.print(", Speed:");Serial.println(Speed);
    //Serial.print(", Position:");Serial.print(Position);
    //Serial.print(", Ax:");Serial.print(Ax);
    //Serial.print(", Ay:");Serial.print(Ay);
    //Serial.print(", Az:");Serial.print(Az);
    //Serial.print(", Total_Accel:");Serial.print(TotalAccel);
    //Serial.print(", AxRaw:");Serial.print(AxRaw);
    //Serial.print(", AyRaw:");Serial.print(AyRaw);
    //Serial.print(", AzRaw:");Serial.print(AzRaw);
  //Serial.print(", Speed SP:");Serial.print(SpeedSP);
  //Serial.print(", Error:");Serial.print(Error);
  //Serial.print(", P Action:");Serial.print(GainOut);
  //Serial.print(", I Action:");Serial.print(IntegralOut);
  //Serial.print(", D Action:");Serial.print(DerivativeOut);
  //Serial.print(", Brake Output:");Serial.print(BrakeCntrl);
  //Serial.println (", Millis:");Serial.println(millis());

//!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!
 }


 //*********   PID Control   *********
 if (Auto == true) {
  Error = max(0, (Speed * 33.3) - SpeedSP); //50 is the
conversion to 100% where 2m/s = 100%
  GainOut = Error * P_Val;
  if (Error > 0) {
   IntegralOut = IntegralOut + Error * I_Val;
  }
  else {
   IntegralOut = 0;
  }
  DerivativeOut = Error * max(0, (TotalAccel - 100)) * D_Val;
  PIDOut = DerivativeOut + IntegralOut + GainOut;
  BrakeCntrl = round(PIDOut * 2.55);
  //  If while breaking the strain gauge measures an increase in
force which may cause impact, then apply brake fully
  if (StrainGauge > 1.0) {
   BrakeCntrl = 255;
  }
  analogWrite(BrakePwm, BrakeCntrl); //Writes the analogue to
the output pin (11).
 }

 if (BrakeOn == true) {
  Braking();  //goto braking function (applies brake/ratchet)

 }
 else if (BrakeOn == false && Manual == false && Auto == false) {
  analogWrite(BrakePwm, 0); //This ensures that brake is turned
off!!!

 }

 else if (Manual == true) {

  //!!!!!!!Manual Control
  BrakeCntrl = round(ManSP * 2.55); // Could be used for manual
torque control.!!!!!!!!!!NOTE ManSP ALWAYS 0 UNTIL WRITTEN
FROM~~~~~~~~~~~!!!!!!!!!!!!!!!
  analogWrite(BrakePwm, BrakeCntrl); //Writes the analogue to
the output pin (11).
 }
 else if (Manual == false && Auto == false && BrakeOn == false) {
  BrakeCntrl = 0;
 }
 TimingMilli2 = millis();
 //Serial.print(StrainGauge);Serial.println(TimingMilli2-
TimingMilli1);//Uncomment to have the scan time printed on the
serial monitor
```

```
}
//***********************     END OF MAIN   **********************


//********************BRAKE RATCHET FUNCTION *********************
/*
 * While the brake is on, if in ratchet mode, if the arm is moving
towards to head, then brake. If while braking the
 * strain gauge reads a force away from head, then release the
brake (otherwise brake).
 *
 * POSITION MAXIMUM ON THE RATCHET SO THAT IT DOESN'T LOCK THEM IN
TOO OPEN A POSITION
 */

void Braking() {
  if (Ratchet == true) {  //If the ratchet is on, then allow only
forward movement until 90 degrees is reached (which is seen as a
safe distance)

    if ((StrainGauge > 0.10 || Speed > 0.2) && Position < 90) {
//!!!!!!!!!!!!!!determine from demo trials
      analogWrite(BrakePwm, 255);
    }
    else if (StrainGauge < -0.15) {
      analogWrite(BrakePwm, 0);
    }
    else if (Position < 50) {
      analogWrite(BrakePwm, 255);
    }
  }
  else {
    analogWrite(BrakePwm, 255);

  }
}
```

LCD Display

```
  //*******************LCD Display Buttons
************************
  //***** The following code is for the plugin LCD backup display
used as a backup to the bluetooth Phone connection
******************************************************************
***


  //A0 is the analogue value for the buttons. Different resisters
for each button gives a different analogue value
  int x = analogRead (0);
  //Set the Row 0, Col 0 position.
  lcd.setCursor(0, 0);

  //Check analog values from LCD Keypad Shield
  if (x < 100) {
    //Right (Actual ~ 002)
    state = 4;
  } else if (x < 300) {
    //Up (Actual ~ 207)
    state = 1;
  } else if (x < 500) {
    //Down (Actual ~ 409)
    state = 2;
  } else if (x < 700) {
    //Left (Actual ~ 631)
    state = 5;
  } else if (x < 900) {
    //Select (Actual ~ 828)
    state = 3;
  }
  else {
    //
    state = 0;
  }
  //********************** SUBMENU SETTINGS **********************
  //******************LCD SPEED SETTING *********************
  if (state != lastState && currentMenuItem == 1 && subMenu ==
true) { //when in submenu 1
    lcd.setCursor(10, 1); //second line
    lcd.print(speedSP);
    if (state == 1) {
      //If Up
      speedSP = speedSP + 1;
    } else if (state == 2) {
      //If Down
      speedSP = speedSP - 1;
    } else if (state == 5) {
      //If back
      subMenu = false;//go back to Main menu
      displayMenu(currentMenuItem);
    }
    //Save the last state to compare.

    lastState = state;
  }
  //******************* FORCE SETTING ************************
  if (state != lastState && currentMenuItem == 2 && subMenu ==
true) { //When in submenu 2
    lcd.setCursor(10, 1);
    lcd.print(forceSP);
    if (state == 1) {
      //If Up
      forceSP = forceSP + 1;
    }
    else if (state == 2) {
      //If Down
      forceSP = forceSP - 1;
    }
    else if (state == 5) {
      //If back
      subMenu = false;//submenu refers to the inner level
      displayMenu(currentMenuItem);
    }
    //Save the last state to compare.

    lastState = state;
  }
  //****************** LOCK OPEN SETTING? ******************
  if (state != lastState && currentMenuItem == 3 && subMenu ==
true) { //When in sub Menu 3
    lcd.setCursor(11, 1);
    if (lockOpen == true) {
      lcd.print("Yes");
    }
    else if (lockOpen == false) {
      lcd.print("No ");
    }
    if (state == 1 || state == 2) {
      //If Up OR Down
      lockOpen = !lockOpen;

    }
    else if (state == 5) {
      //If back
      subMenu = false;// Go back to Main Menu
      displayMenu(currentMenuItem);
    }
    //Save the last state to compare.

    lastState = state;
  }
  //****************** TURN OFF SETTING ******************
  if (state != lastState && currentMenuItem == 4 && subMenu ==
true) { //When in Sub Menu 4
    lcd.setCursor(11, 1);
    if (DSDOff == true) {
      lcd.print("Yes");
    }
    else if (DSDOff == false) {
      lcd.print("No ");

    }
    if (state == 1 || state == 2) {
      //If Up OR down
      DSDOff = !DSDOff;

    }
    else if (state == 5) {
      //If back
      subMenu = false;//submenu refers to the inner level
      displayMenu(currentMenuItem);
    }
    //Save the last state to compare.

    lastState = state;
  }

  //****** FOR BATTERY SAVING, ONLY TURN LIGHT ON FOR 10 SEC ON
KEY PRESS*****
  if (state != 0) {
    pinMode(10, INPUT); //PIN 10 is the LCD light. Changing to
input turns off and grounds !!CHECK!!!!!!
    light = true;
  }
  currentMillis = millis();
  if (currentMillis - previousMillis > 10000) {
    previousMillis = currentMillis;
    pinMode(10, OUTPUT); //Changing to output turns light on.
    light = false;
  }
  //*******************  LCD MAIN MENU
*******************************



  //If we have changed Index, saves re-draws.
  if (state != lastState && subMenu == false) {
    if (state == 1) {
      //If Up
      currentMenuItem = currentMenuItem + 1;

      displayMenu(currentMenuItem);
    }
    else if (state == 2) {
      //If Down
      currentMenuItem = currentMenuItem - 1;
      displayMenu(currentMenuItem);
    }
    else if (state == 3) {
      //If Selected
      subMenu = true;//submenu refers to the inner level
      selectMenu(currentMenuItem);
    }
    else if (state == 4 || (recd_dat == 'CA' ))
{//*******************CALIBRATE****************
      //If right Selected
      currentMenuItem = 0;
      subMenu = false;
      accelero.calibrate();
    }
    //Save the last state to compare.
    lastState = state;

    //If we are out of bounds on the menu then rotate it through.
    if (currentMenuItem < 1) {
      currentMenuItem = 4;
      displayMenu(currentMenuItem);
    }
    if (currentMenuItem > 4) {
      currentMenuItem = 1;
      displayMenu(currentMenuItem);
    }
  }


//***************************     END OF MAIN!!!!!!   FUNCTIONS
BELOW

//Display Menu Option based on Index.
void displayMenu(int dispNum) {
  switch (dispNum) {
    case 1:
      clearPrintTitle();
      lcd.print ("-> Speed Control");
      break;
    case 2:
      clearPrintTitle();
      lcd.print ("-> Force Control");
      break;
    case 3:
      clearPrintTitle();
      lcd.print ("-> Lock OPEN");
      break;
    case 4:
      clearPrintTitle();
      lcd.print ("-> OFF");
      break;
  }
}

//Print a basic header on Row 1.
void clearPrintTitle() {
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("USQ PROJECT: DSD");
  lcd.setCursor(0, 1);
}

//Show the selection on Screen.
void selectMenu(int SelectNum) {
  switch (SelectNum) {
    case 1:
      clearPrintTitle();
      lcd.print ("Speed SP:");
      //Call the function that belongs to speed SP
      break;
    case 2:
      clearPrintTitle();
      lcd.print ("Force SP:");
      //Call the function that belongs to Force SP
      break;
    case 3:
      clearPrintTitle();


      lcd.print ("Lock Open?");


      //Call the function that belongs to Lock Open
      break;
    case 4:
```

```
clearPrintTitle();
lcd.print ("Turn OFF?");
//Call the function that belongs to Turn Off
break;
```

Appendix E- Arduino Arm Movement Raw Data

	The following is 4 slow movements, then 4 impacts (with the last being the hardest) using NO FILTER											
Strain	Speed	Position	CalcAcc	Ax	Ay	Az	Total Acc	/10	AxRaw	AyRaw	AzRaw	Millis
9.2	-77	137.29		-35	-88	0	94.7	14.7	-35	-88	0	1069
11.6	-27	144.68	34.48276	-38	-85	-1	93.11	13.11	-38	-85	-1	1214
13.7	-8	146.79	13.28671	-39	-77	4	86.41	6.41	-39	-77	4	1357
11.6	8	144.68	11.18881	-36	-70	3	78.77	-1.23	-36	-70	3	1500
21.7	-5	146.09	9.027778	-38	-81	5	89.61	9.61	-38	-81	5	1644
16.6	-18	151.01	8.965517	-47	-72	-6	86.19	6.19	-47	-72	-6	1789
16.4	-5	152.42	9.027778	-41	-74	2	84.62	4.62	-41	-74	2	1933
14	8	150.31	9.15493	-40	-82	7	91.5	11.5	-40	-82	7	2075
28.6	4	149.25	2.816901	-38	-78	4	86.86	6.86	-38	-78	4	2217
32.5	-8	151.36	8.333333	-42	-81	3	91.29	11.29	-42	-81	3	2361
28.6	4	150.31	8.275862	-40	-81	10	90.89	10.89	-40	-81	10	2506
23	-5	151.72	6.25	-40	-83	9	92.57	12.57	-40	-83	9	2650
25.3	9	149.25	9.722222	-37	-79	11	87.93	7.93	-37	-79	11	2794
28.9	0	149.25	6.25	-37	-79	12	88.06	8.06	-37	-79	12	2938
32	-3	149.96	2.054795	-37	-78	12	87.16	7.16	-37	-78	12	3084
32.5	3	149.25	4.166667	-34	-80	11	87.62	7.62	-34	-80	11	3228
32.8	13	145.73	6.849315	-32	-83	17	90.56	10.56	-32	-83	17	3374
33.5	0	145.73	9.027778	-33	-80	18	88.39	8.39	-33	-80	18	3518
30.6	-10	148.55	6.896552	-32	-78	17	86.01	6.01	-32	-78	17	3663
26.5	1	148.2	7.586207	-33	-80	17	88.19	8.19	-33	-80	17	3808
31.8	8	146.09	4.861111	-34	-79	16	87.48	7.48	-34	-79	16	3952
34.1	4	145.03	2.758621	-35	-79	17	88.06	8.06	-35	-79	17	4097
36.3	-1	145.38	3.424658	-33	-81	17	89.1	9.1	-33	-81	17	4243
34.3	-9	147.84	5.517241	-36	-78	13	86.88	6.88	-36	-78	13	4388

Strain	Speed	Position	CalcAcc	Ax	Ay	Az	Total Acc	/10	AxRaw	AyRaw	AzRaw	Millis
28.8	0	147.84	6.206897	-38	-77	15	87.17	7.17	-38	-77	15	4533
23.7	5	146.44	3.472222	-39	-77	13	87.29	7.29	-39	-77	13	4677
23.4	-1	146.79	4.109589	-39	-78	14	88.32	8.32	-39	-78	14	4823
22.6	-8	148.9	4.794521	-40	-78	13	88.62	8.62	-40	-78	13	4969
27.2	0	148.9	5.555556	-39	-79	14	89.21	9.21	-39	-79	14	5113
32	9	146.44	6.206897	-37	-79	14	88.35	8.35	-37	-79	14	5258
33.9	15	142.21	4.166667	-33	-87	13	93.95	13.95	-33	-87	13	5402
38	58	126.38	29.65517	-21	-94	13	97.19	17.19	-21	-94	13	5547
46.1	89	101.74	22.46377	0	-88	3	88.05	8.05	0	-88	3	5685
50.4	105	73.94	11.34752	20	-66	-7	69.32	-10.68	20	-66	-7	5826
58.4	86	50.72	13.38028	40	-61	-7	73.28	-6.72	40	-61	-7	5968
67.6	54	35.94	22.53521	54	-53	-8	76.09	-3.91	54	-53	-8	6110
73	30	27.84	16.78322	57	-51	-10	77.14	-2.86	57	-51	-10	6253
79.8	3	27.14	18.88112	61	-54	-13	82.5	2.5	61	-54	-13	6396
50.8	-5	28.55	5.517241	52	-50	-10	72.83	-7.17	52	-50	-10	6541
28.8	-59	44.74	37.5	40	-65	-11	77.11	-2.89	40	-65	-11	6685
21.1	-79	66.55	13.69863	24	-69	-12	74.03	-5.97	24	-69	-12	6831
18.1	-70	85.91	6.428571	9	-86	-5	86.61	6.61	9	-86	-5	6971
16.3	-74	105.62	2.836879	-8	-85	0	85.38	5.38	-8	-85	0	7112
18.5	-56	120.75	12.5	-17	-84	4	85.8	5.8	-17	-84	4	7256
15.2	-33	129.9	16.08392	-29	-86	7	91.03	11.03	-29	-86	7	7399
14	-28	137.64	3.496503	-31	-90	7	95.45	15.45	-31	-90	7	7542
14	17	133.06	30.82192	-24	-103	3	105.8	25.8	-24	-103	3	7688
35.9	115	100.69	68.53147	-2	-88	-1	88.03	8.03	-2	-88	-1	7831
48.1	141	62.33	18.18182	26	-62	-11	68.12	-11.88	26	-62	-11	7974
59.5	87	38.4	38.02817	50	-48	-8	69.77	-10.23	50	-48	-8	8116
67.4	46	26.09	29.07801	58	-27	-8	64.47	-15.53	58	-27	-8	8257
72.4	3	25.38	30.06993	59	-45	-14	75.51	-4.49	59	-45	-14	8400

Strain	Speed	Position	CalcAcc	Ax	Ay	Az	Total Acc	/10	AxRaw	AyRaw	AzRaw	Millis
52.7	-13	28.9	11.03448	54	-53	-10	76.32	-3.68	54	-53	-10	8545
23.2	-86	52.83	51.40845	32	-61	-8	69.35	-10.65	32	-61	-8	8687
21.8	-118	84.85	22.69504	1	-85	-4	85.1	5.1	1	-85	-4	8828
19.1	-107	113.71	7.638889	-21	-88	0	90.47	10.47	-21	-88	0	8972
16.7	-64	131.3	30.06993	-29	-85	8	90.17	10.17	-29	-85	8	9115
14.3	-44	143.27	13.88889	-40	-86	9	95.27	15.27	-40	-86	9	9259
12.2	-1	143.62	30.06993	-40	-81	9	90.79	10.79	-40	-81	9	9402
12.2	6	141.86	4.827586	-36	-104	6	110.22	30.22	-36	-104	6	9547
23.4	117	109.13	77.62238	-14	-85	2	86.17	6.17	-14	-85	2	9690
46.6	142	70.43	17.60563	19	-70	-7	72.87	-7.13	19	-70	-7	9832
57.8	108	41.22	24.11348	46	-51	-8	69.14	-10.86	46	-51	-8	9973
61.8	41	30.31	46.52778	54	-37	-11	66.38	-13.62	54	-37	-11	10117
68.9	-3	31.01	30.34483	54	-51	-12	75.24	-4.76	54	-51	-12	10262
31.5	-38	41.57	24.13793	45	-67	-11	81.46	1.46	45	-67	-11	10407
22.7	-84	65.15	31.94444	20	-68	-5	71.06	-8.94	20	-68	-5	10551
20.6	-98	91.89	9.722222	-3	-86	-3	86.1	6.1	-3	-86	-3	10695
19.6	-73	111.95	17.24138	-15	-86	3	87.35	7.35	-15	-86	3	10840
19.2	-62	129.19	7.638889	-33	-86	7	92.38	12.38	-33	-86	7	10984
14.5	-28	136.94	23.28767	-38	-83	10	91.83	11.83	-38	-83	10	11130
12.2	-20	142.57	5.517241	-43	-77	9	88.65	8.65	-43	-77	9	11275
12.1	-3	143.27	11.64384	-46	-82	13	94.92	14.92	-46	-82	13	11421
12.6	15	139.05	12.41379	-35	-91	5	97.63	17.63	-35	-91	5	11566
33.7	86	115.47	49.65035	-20	-92	2	94.17	14.17	-20	-92	2	11709
42.2	135	78.52	34.50704	15	-72	-4	73.65	-6.35	15	-72	-4	11851
51.3	108	49.31	18.88112	42	-59	-8	72.86	-7.14	42	-59	-8	11994
59.1	62	32.42	31.94444	46	-50	-11	68.83	-11.17	46	-50	-11	12138
63.8	33	23.27	20.13889	64	-58	-13	87.34	7.34	64	-58	-13	12282
79.5	41	12.01	5.555556	71	-33	-5	78.45	-1.55	71	-33	-5	12426

Strain	Speed	Position	CalcAcc	Ax	Ay	Az	Total Acc	/10	AxRaw	AyRaw	AzRaw	Millis
90.2	3	11.3	26.38889	62	-44	-12	76.97	-3.03	62	-44	-12	12570
84.4	5	9.9	1.398601	65	-46	-12	80.53	0.53	65	-46	-12	12713
85.8	1	9.55	2.816901	65	-39	-6	76.04	-3.96	65	-39	-6	12855
59.5	-29	17.29	20.68966	56	-46	-10	73.16	-6.84	56	-46	-10	13000
34.7	-99	44.74	47.94521	33	-61	-11	70.22	-9.78	33	-61	-11	13146
24.5	-115	77.11	11.11111	8	-87	-10	87.94	7.94	8	-87	-10	13290
20.3	-76	97.87	27.27273	-2	-87	-5	87.17	7.17	-2	-87	-5	13433
17.5	-65	115.82	7.586207	-19	-83	3	85.2	5.2	-19	-83	3	13578
16.1	-69	134.82	2.777778	-33	-88	8	94.32	14.32	-33	-88	8	13722
15.2	-40	145.73	20	-41	-83	8	92.92	12.92	-41	-83	8	13867
13.3	-18	150.66	15.06849	-49	-75	10	90.14	10.14	-49	-75	10	14013
9.4	-11	153.83	4.794521	-49	-75	13	90.53	10.53	-49	-75	13	14159
7.2	-13	157.35	1.388889	-51	-75	9	91.14	11.14	-51	-75	9	14303
8.4	4	156.29	11.72414	-53	-97	12	111.18	31.18	-53	-97	12	14448
25.5	119	123.21	78.23129	-34	-133	7	137.46	57.46	-34	-133	7	14595
43.8	323	32.42	140.6897	26	212	233	316.08	236.08	26	212	233	14740
51	-6	34.18	225.3425	29	-12	-14	34.37	-45.63	29	-12	-14	14886
18.2	-134	71.48	87.67123	11	-87	-13	88.65	8.65	11	-87	-13	15032
19.3	-109	101.74	17.36111	-10	-87	1	87.58	7.58	-10	-87	1	15176
19.1	-79	123.56	20.68966	-33	-91	2	96.82	16.82	-33	-91	2	15321
17.8	-50	137.29	19.72789	-42	-90	15	100.44	20.44	-42	-90	15	15468
16.7	7	135.18	38	-39	-114	11	120.99	40.99	-39	-114	11	15618
36.1	277	56.35	187.5	14	-71	-15	73.91	-6.09	14	-71	-15	15762
47.1	113	25.38	111.5646	42	-105	-33	117.8	37.8	42	-105	-33	15909
19.2	-67	44.38	125	28	-65	-5	70.95	-9.05	28	-65	-5	16053
10.8	-126	78.87	41.84397	3	-89	-8	89.41	9.41	3	-89	-8	16194
16.6	-99	105.62	18.75	-19	-89	3	91.05	11.05	-19	-89	3	16338
22.3	-49	119.34	34.24658	-28	-93	5	97.25	17.25	-28	-93	5	16484

Strain	Speed	Position	CalcAcc	Ax	Ay	Az	Total Acc	/10	AxRaw	AyRaw	AzRaw	Millis
21.6	-9	121.8	27.21088	-30	-100	7	104.64	24.64	-30	-100	7	16631
21.3	125	86.61	89.33333	-66	-192	-11	203.32	123.32	-66	-192	-11	16781
39.2	210	26.44	60.28369	95	47	34	111.31	31.31	95	47	34	16922
21.3	-71	45.44	199.2908	32	-75	0	81.54	1.54	32	-75	0	17063
11	-125	79.57	37.5	-2	-82	-1	82.03	2.03	-2	-82	-1	17207
16.8	-101	107.02	16.55172	-18	-98	7	99.88	19.88	-18	-98	7	17352
20.6	-63	124.27	26.0274	-35	-97	9	103.51	23.51	-35	-97	9	17498
19.2	4	123.21	45.27027	-33	-122	11	126.86	46.86	-33	-122	11	17646
26.4	329	30.31	219.5946	14	196	-163	255.31	175.31	14	196	-163	17794
41.2	0	30.31	228.4722	27	-32	-17	45.19	-34.81	27	-32	-17	17938
1.7	-109	60.57	74.65753	8	-101	-15	102.42	22.42	8	-101	-15	18084
5.9	-82	83.45	19.14894	-7	-80	0	80.31	0.31	-7	-80	0	18225
14.7	-61	99.63	14.68531	-11	-77	6	78.01	-1.99	-11	-77	6	18368
5.6	-34	108.78	18.88112	-27	-96	7	99.97	19.97	-27	-96	7	18511
1.1	-6	110.54	19.44444	-28	-83	7	87.87	7.87	-28	-83	7	18655
-2.5	-9	113.01	2.054795	-27	-82	11	87.03	7.03	-27	-82	11	18801
6.6	4	111.95	9.027778	-26	-88	7	92.03	12.03	-26	-88	7	18945
14.5	15	107.73	7.692308	-23	-77	1	80.37	0.37	-23	-77	1	19088
22.2	39	97.17	16.90141	-16	-78	9	80.13	0.13	-16	-78	9	19230
26.2	21	91.54	12.58741	-11	-86	9	87.17	7.17	-11	-86	9	19373
25.5	17	86.96	2.777778	-15	-84	12	86.17	6.17	-15	-84	12	19517
35.3	15	82.74	1.388889	-15	-84	11	86.03	6.03	-15	-84	11	19661
36.7	6	80.98	6.206897	-18	-82	12	84.81	4.81	-18	-82	12	19806
36.7	0	80.98	4.137931	-18	-84	13	86.88	6.88	-18	-84	13	19951
35.2	-4	82.04	2.739726	-16	-85	13	87.46	7.46	-16	-85	13	20097
33.2	0	82.04	2.777778	-16	-83	11	85.24	5.24	-16	-83	11	20241
32.7	5	80.63	3.472222	-16	-83	13	85.52	5.52	-16	-83	13	20385
30.2	0	80.63	3.448276	-16	-84	13	86.49	6.49	-16	-84	13	20530

Strain	Speed	Position	CalcAcc	Ax	Ay	Az	Total Acc	/10	AxRaw	AyRaw	AzRaw	Millis
27.4	-6	82.39	4.109589	-19	-83	14	86.29	6.29	-19	-83	14	20676
27.1	0	82.39	4.166667	-19	-86	10	88.64	8.64	-19	-86	10	20820
25	6	80.63	4.137931	-19	-84	11	86.82	6.82	-19	-84	11	20965
22.3	-1	80.98	4.895105	-14	-82	9	83.67	3.67	-14	-82	9	21108
19.5	1	80.63	1.398601	-15	-86	7	87.58	7.58	-15	-86	7	21251
13	-6	82.39	4.895105	-15	-82	7	83.65	3.65	-15	-82	7	21394
11.1	0	82.39	4.225352	-17	-84	7	85.99	5.99	-17	-84	7	21536
10.9	6	80.63	4.166667	-16	-84	6	85.72	5.72	-16	-84	6	21680
11.5	0	80.63	4.225352	-15	-84	7	85.62	5.62	-15	-84	7	21822
10.5	-5	82.04	3.496503	-17	-83	6	84.94	4.94	-17	-83	6	21965
10.4	0	82.04	3.496503	-16	-85	6	86.7	6.7	-16	-85	6	22108
6.2	5	80.63	3.546099	-19	-85	7	87.38	7.38	-19	-85	7	22249
6.7	0	80.63	3.546099	-16	-82	4	83.64	3.64	-16	-82	4	22390
6.2	0	80.63	0	-16	-83	6	84.74	4.74	-16	-83	6	22532
6	-5	82.04	3.496503	-15	-84	4	85.42	5.42	-15	-84	4	22675
2.9	-1	82.39	2.816901	-16	-84	5	85.66	5.66	-16	-84	5	22817
3.1	5	80.98	4.225352	-14	-84	5	85.31	5.31	-14	-84	5	22959
1.1	0	80.98	3.546099	-17	-83	3	84.78	4.78	-17	-83	3	23100
3.7	-5	82.39	3.521127	-15	-76	5	77.63	-2.37	-15	-76	5	23242
6.2	0	82.39	3.521127	-16	-81	0	82.57	2.57	-16	-81	0	23384
11.5	4	81.33	2.816901	-17	-82	2	83.77	3.77	-17	-82	2	23526
11.9	1	80.98	2.068966	-16	-84	11	86.21	6.21	-16	-84	11	23671
19.4	-5	82.39	4.109589	-15	-85	11	87.01	7.01	-15	-85	11	23817
26.4	-1	82.74	2.797203	-16	-83	9	85.01	5.01	-16	-83	9	23960
26.1	0	82.74	0.694444	-16	-83	10	85.12	5.12	-16	-83	10	24104
18.7	6	80.98	4.137931	-17	-81	10	83.37	3.37	-17	-81	10	24249
10.9	-4	82.04	6.993007	-19	-80	6	82.44	2.44	-19	-80	6	24392
4.2	-5	83.45	0.684932	-18	-84	14	87.04	7.04	-18	-84	14	24538

0.8	-5	89.43	0	-17.65	-83.5	12.82	86.31	6.31	-18	-83	13	24711

Appendix F- Phone Application Variables

Table F-1: Phone Application Variables

Graphic Group Name	Variable Name	Variable Type
HzBt	BtPicker	List Picker
	BnExit	Button
HzBrakeOn	BnBrakeOn	Button
CbRatchet		Check Box
HzSpOn	TxSpOn	Label
	BnSpOn	Button
HzSpSp	TxSpSp	Label
	SlSc	Slider
HzSpInput	TxInputSp	Text Box
	BnSpSet	Button
HzFcOn	TxFcOn	Label
	BnFcOn	Button
HzFcSp	TxFcSp	Label
	SlFc	Slider
HzFcInput	TxInputFc	Text Box
	BnFcSet	Button
HzRs	TxMaxSp	Label
	TxMaxFc	Label
	TxPos	Label
	BnRs	Button
HzCal	TxDisMaxSp	Label
	TxDispMaxFc	Label
	TxDisPos	Label
	BnCal	Button
BluetoothClient1		Bluetooth Client
Clock1		Clock
NotCal		Notifier
NotReset		Notifier
Vibrate		Sound (Vibrate)
Notifier_General		Notifier
NotExit		Notifier
Alert		Sound